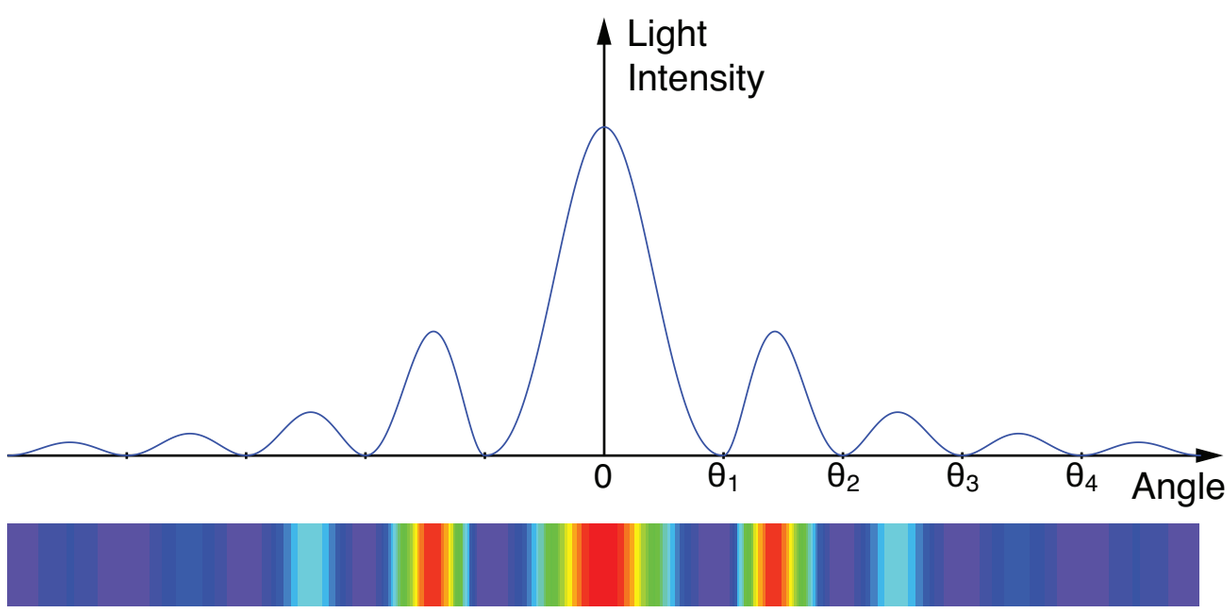
BROOKHAVEN NATIONAL LABORATORY

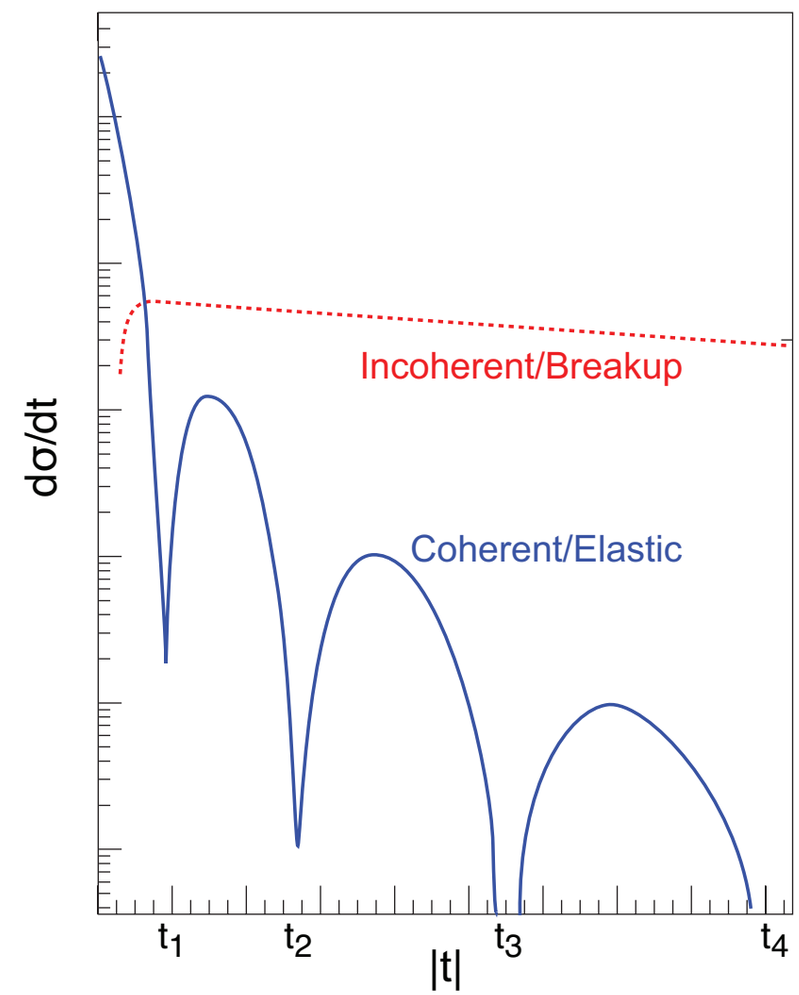
eRHIC

Probing spatial gluon distributions in heavy nuclei

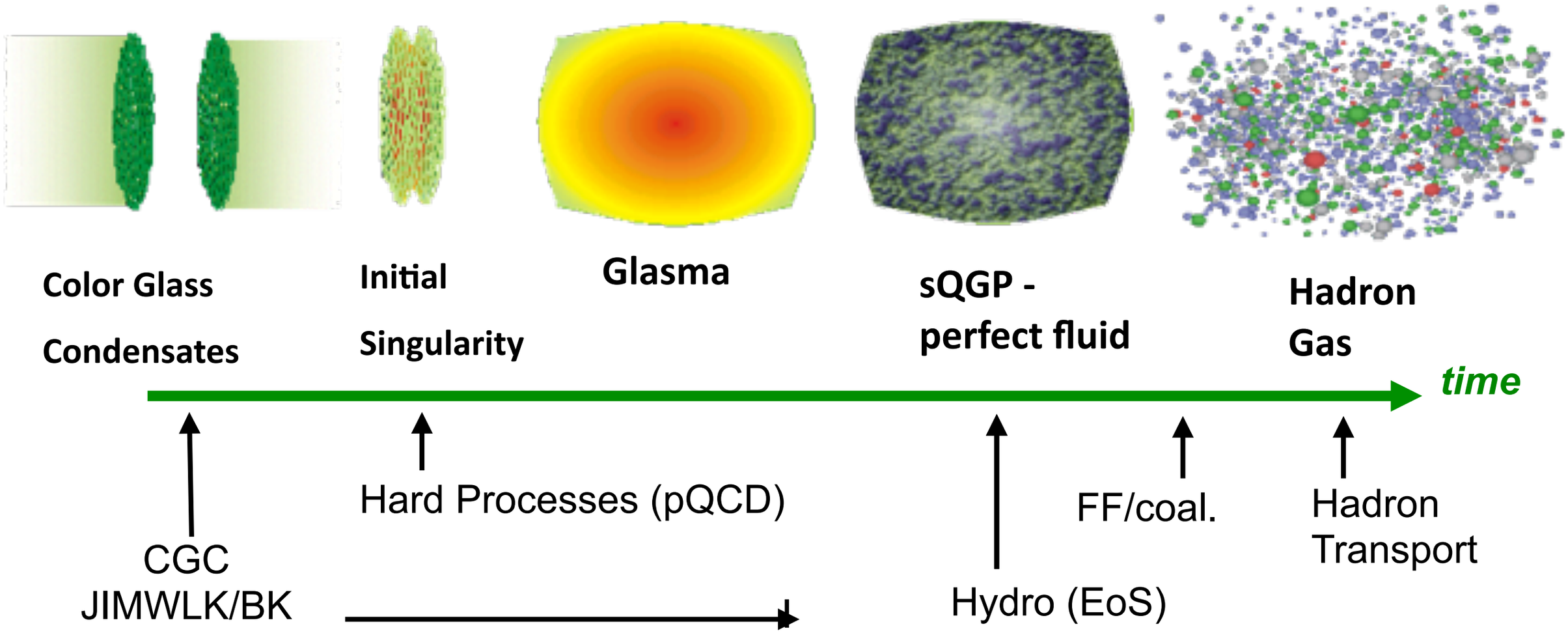
Hot Quarks 2012

Tobias Toll





"Standard model of Heavy Ion Collisions"



Our understanding of some fundamental properties of the Glasma, sQGP and Hadron Gas depend strongly on our knowledge of the initial state!

3 conundrums of the initial state:

1. What is the spatial transverse distributions of gluons?
2. How much does the spatial distribution fluctuate? Lumpiness, hot-spots etc.
3. How saturated is the initial state of the nucleus?

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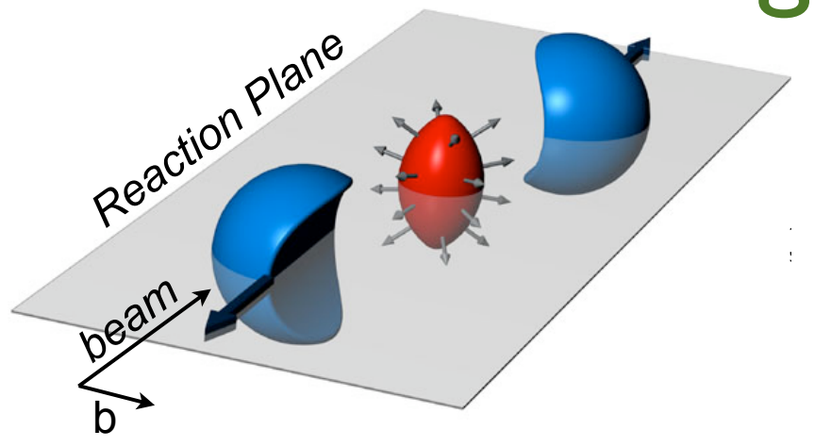
Different initial distributions gives different flows!

$$\epsilon_2 = \frac{\langle y^2 - x^2 \rangle}{\langle y^2 + x^2 \rangle}$$



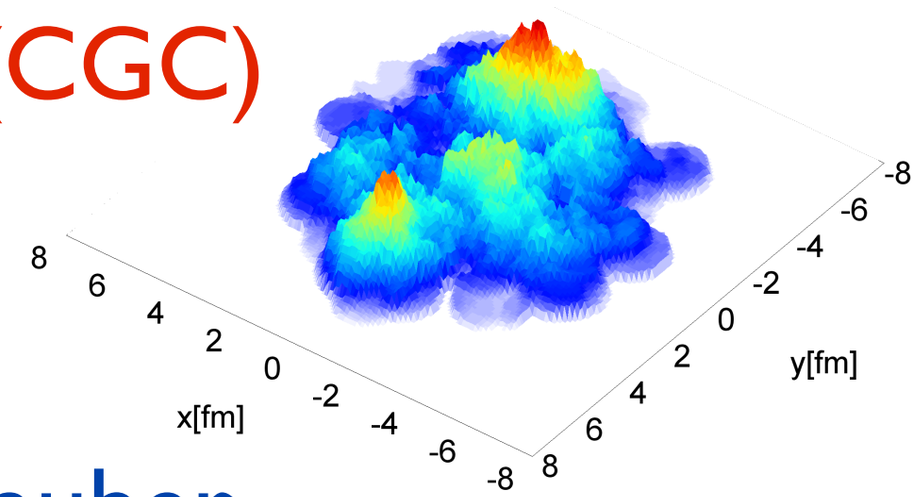
The question is what is ε?

RHIC & LHC: low-p_T realm driven almost entirely by glue ⇒ spatial distribution of glue in nuclei?

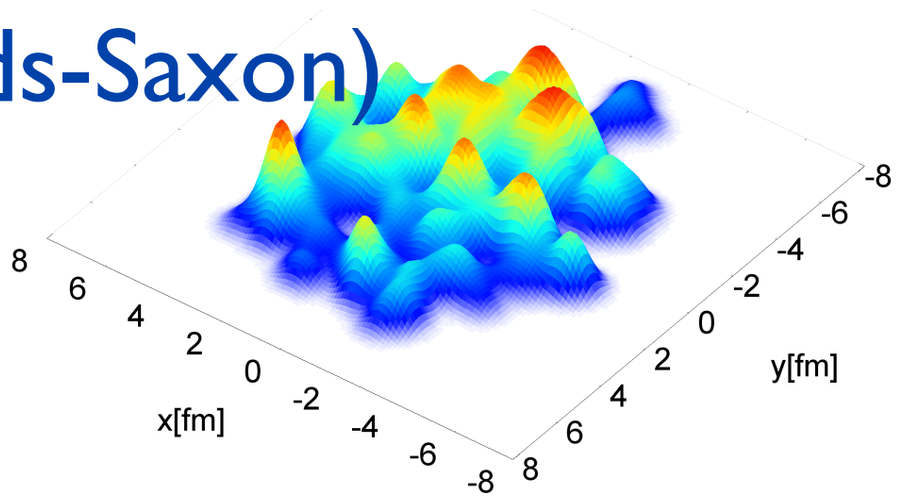
Two methods for ε:

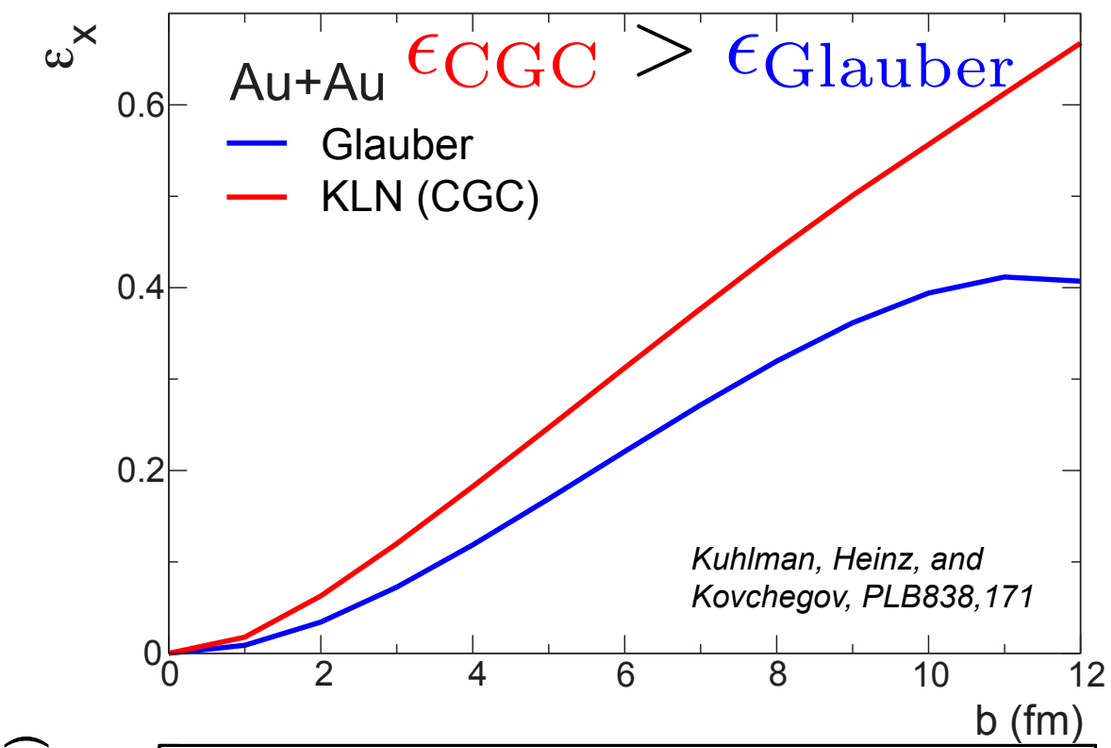
- Glauber (non-saturated)
- CGC (saturated)

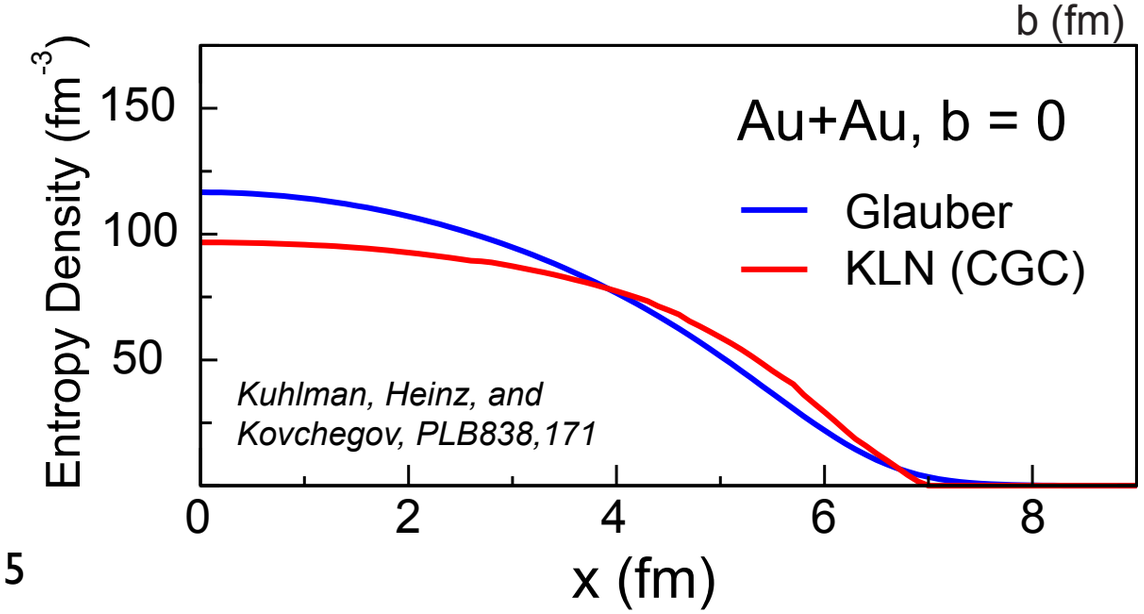
KLN(CGC)



Glauber (Woods-Saxon)







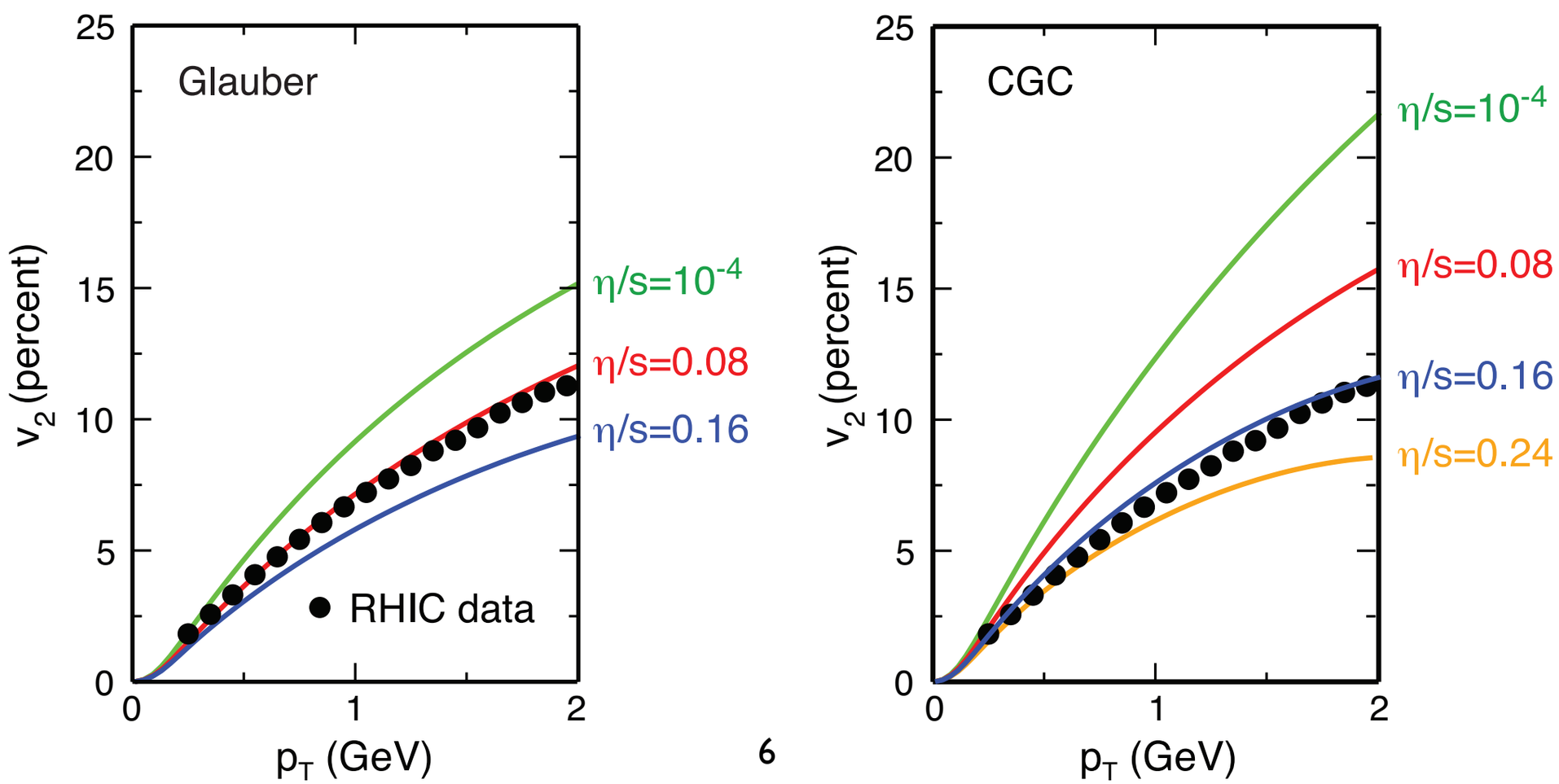
Is the sQGP a perfect fluid?

AdS/CFT predicts for a perfect fluid:

$\eta/s = 1/(4\pi) \sim 0.08$

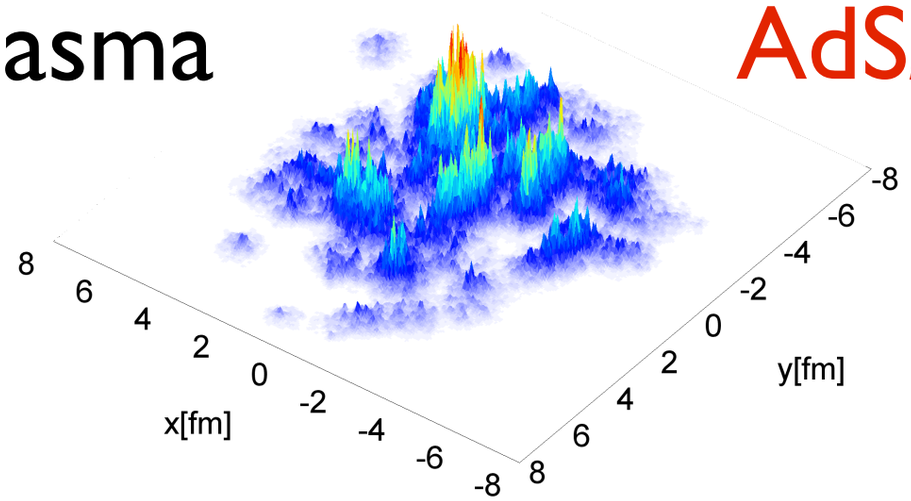
Different initial geometries of nuclei gives different η/s of the strongly coupled Quark-Gluon Plasma

How "perfect" is the fluid?

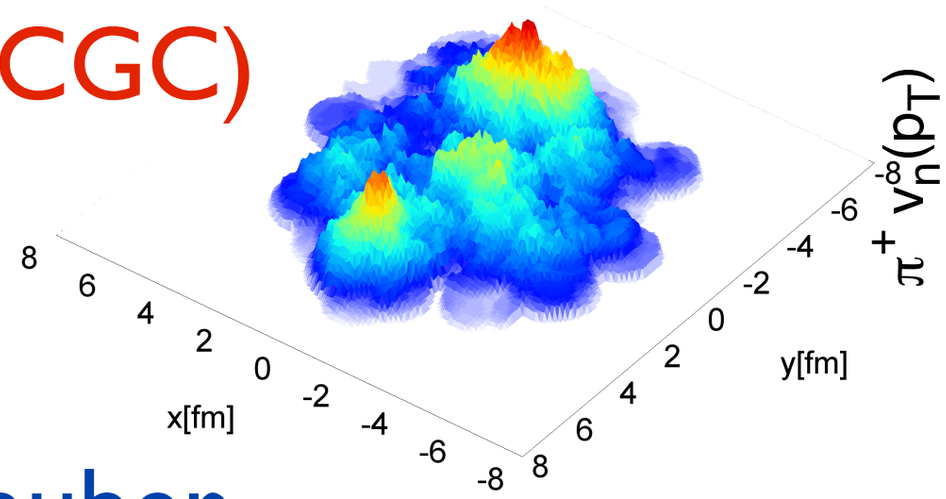


Is the sQGP a perfect fluid?

IP-Glasma



KLN(CGC)



Glauber
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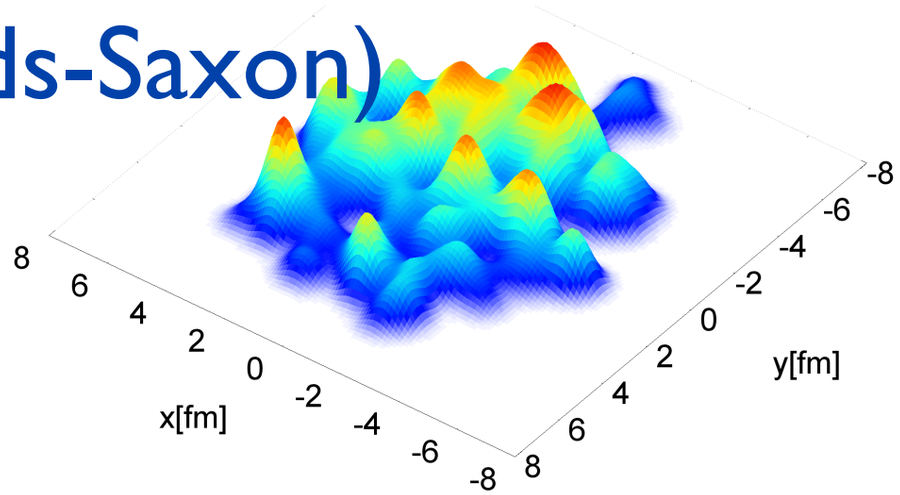

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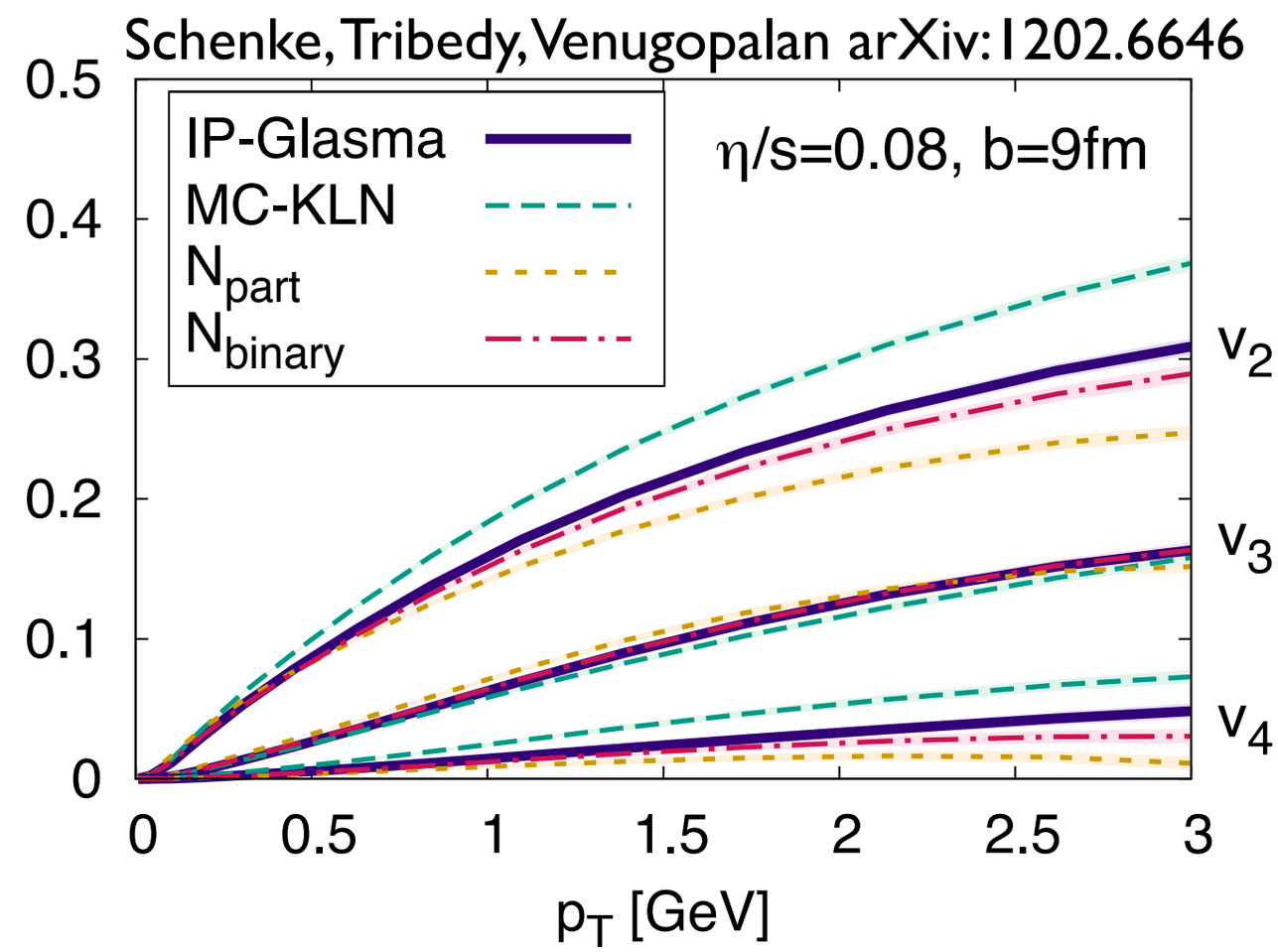


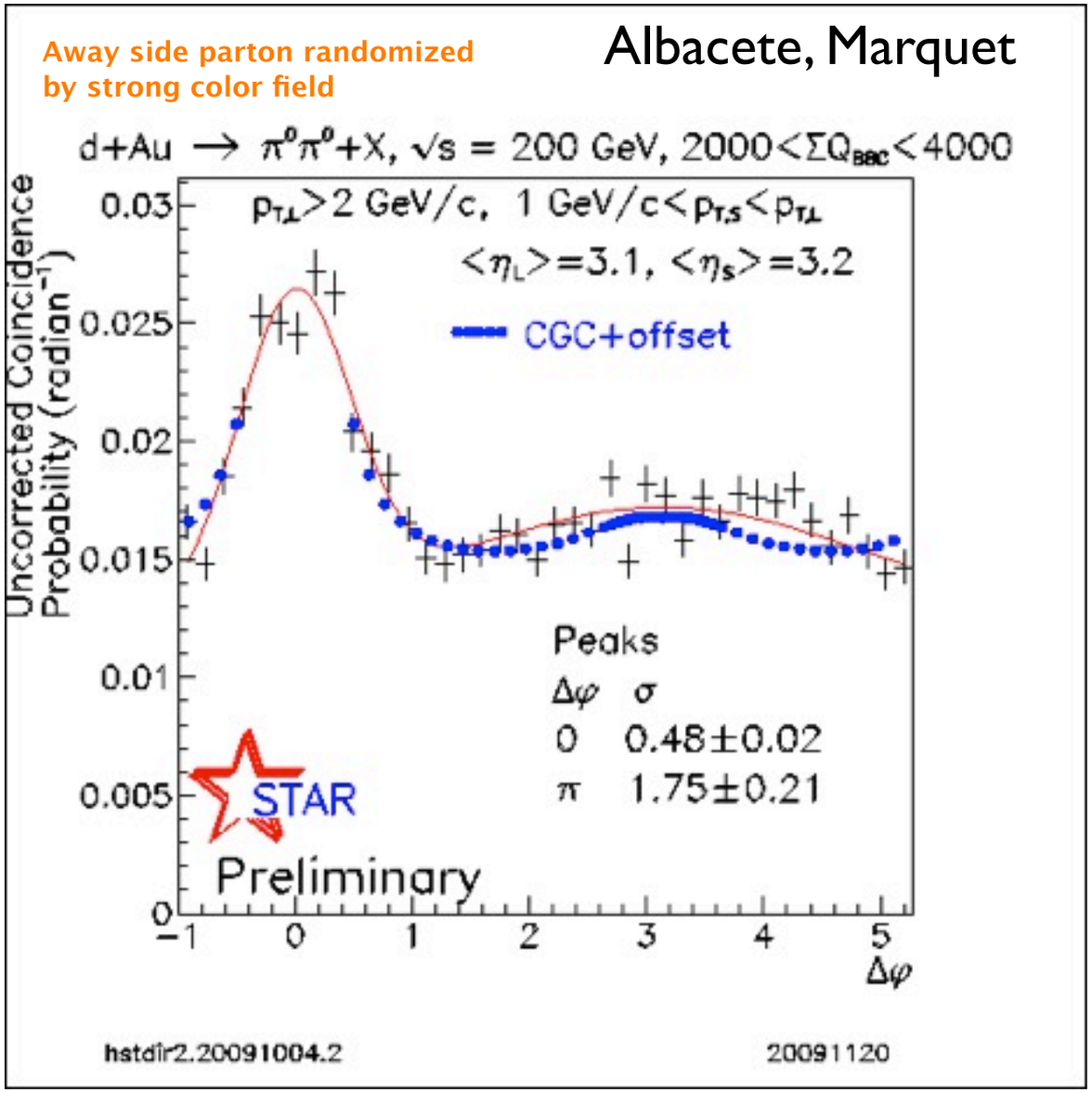
Different initial states=
different fluctuation scales

3 conundrums of the initial state:

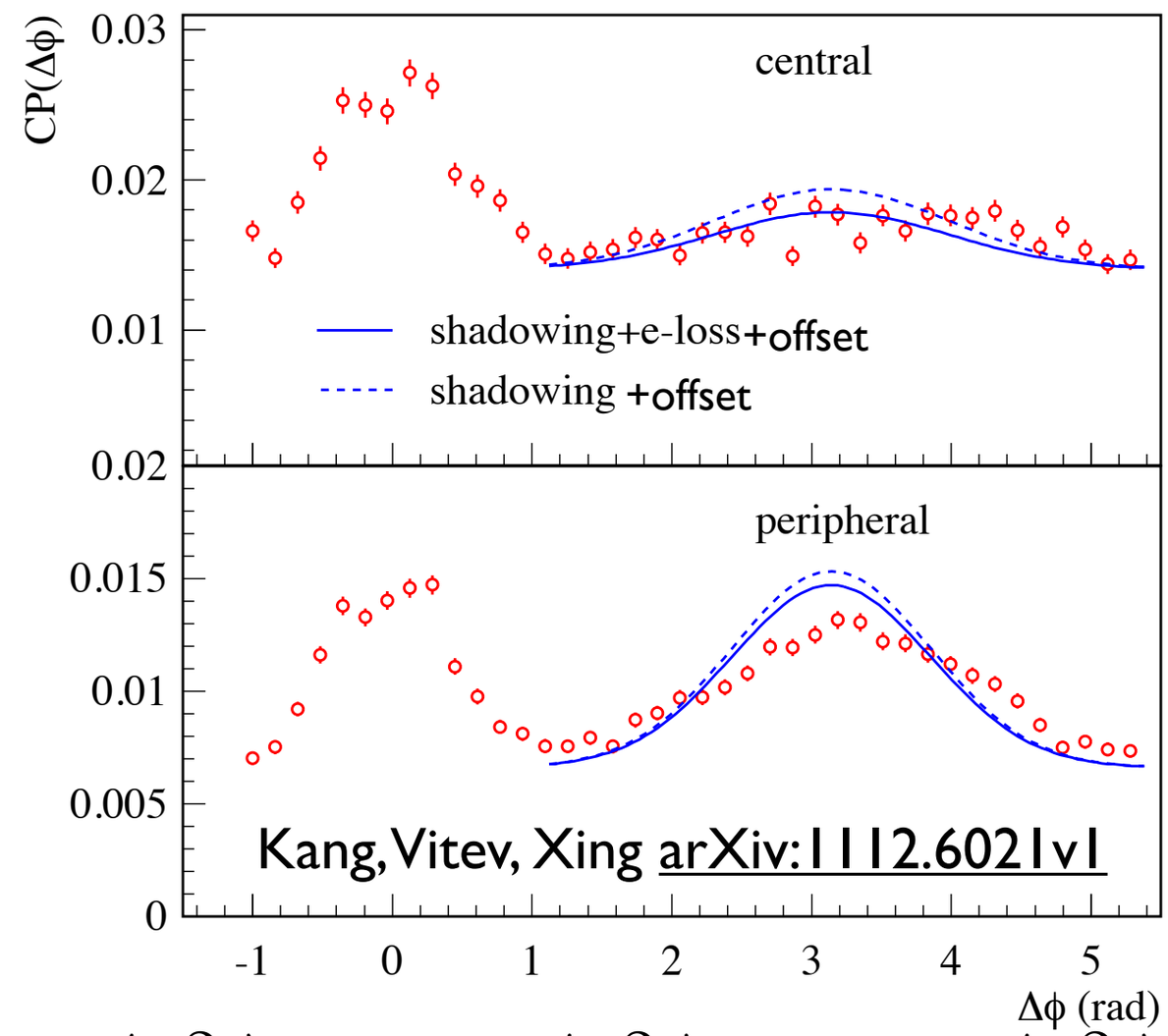
1. What is the spatial transverse distributions of nucleons and gluons?
2. How much does the spatial distribution fluctuate? Lumpiness, hot-spots etc.
3. How saturated is the initial state of the nucleus?

1 question, 2 answers

Initial state saturation model



Initial and final state multiple scattering

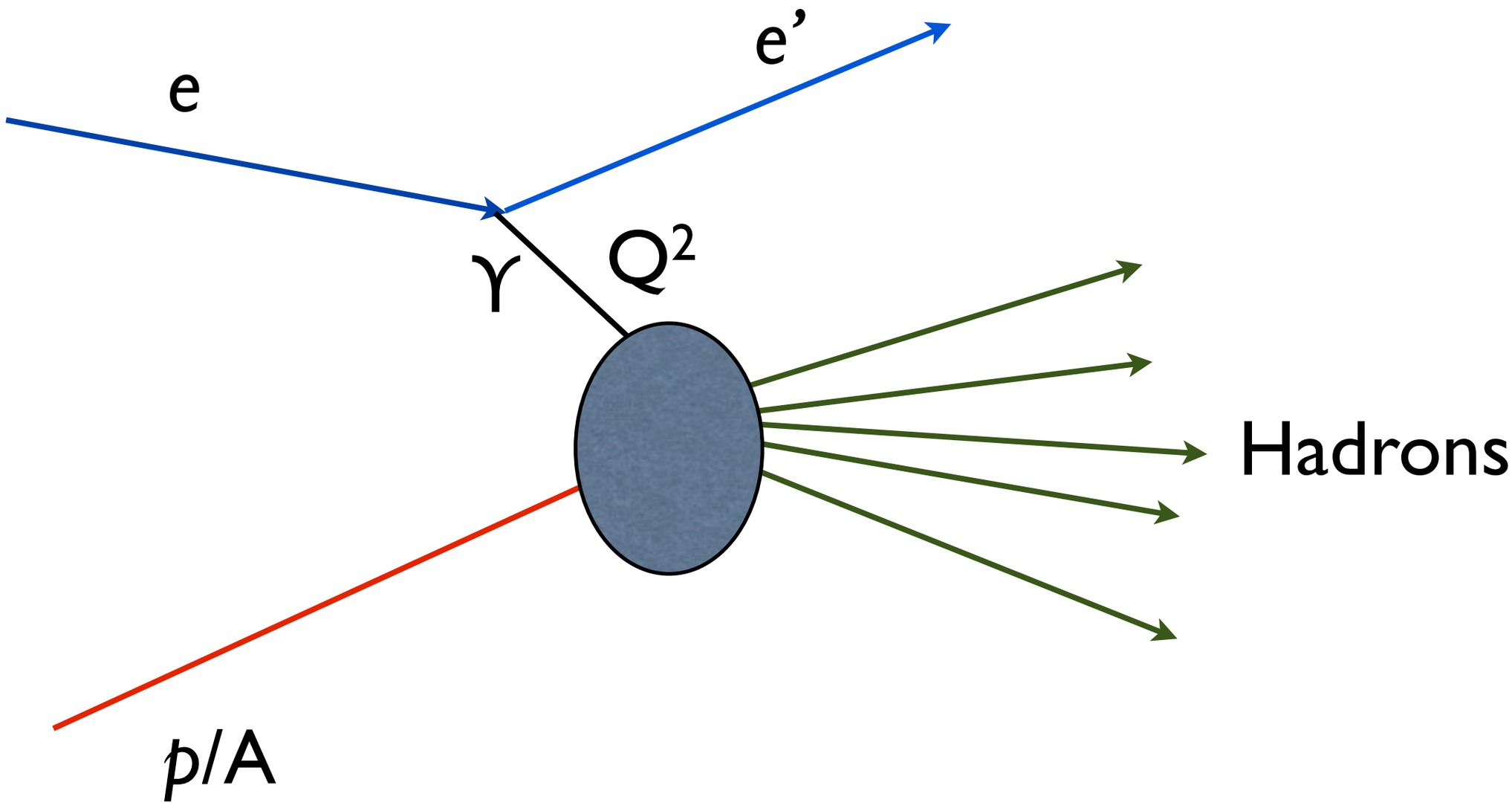


$$\langle q_\perp^2 \rangle_{dAu} = \langle q_\perp^2 \rangle_{pp} + \Delta \langle q_\perp^2 \rangle$$

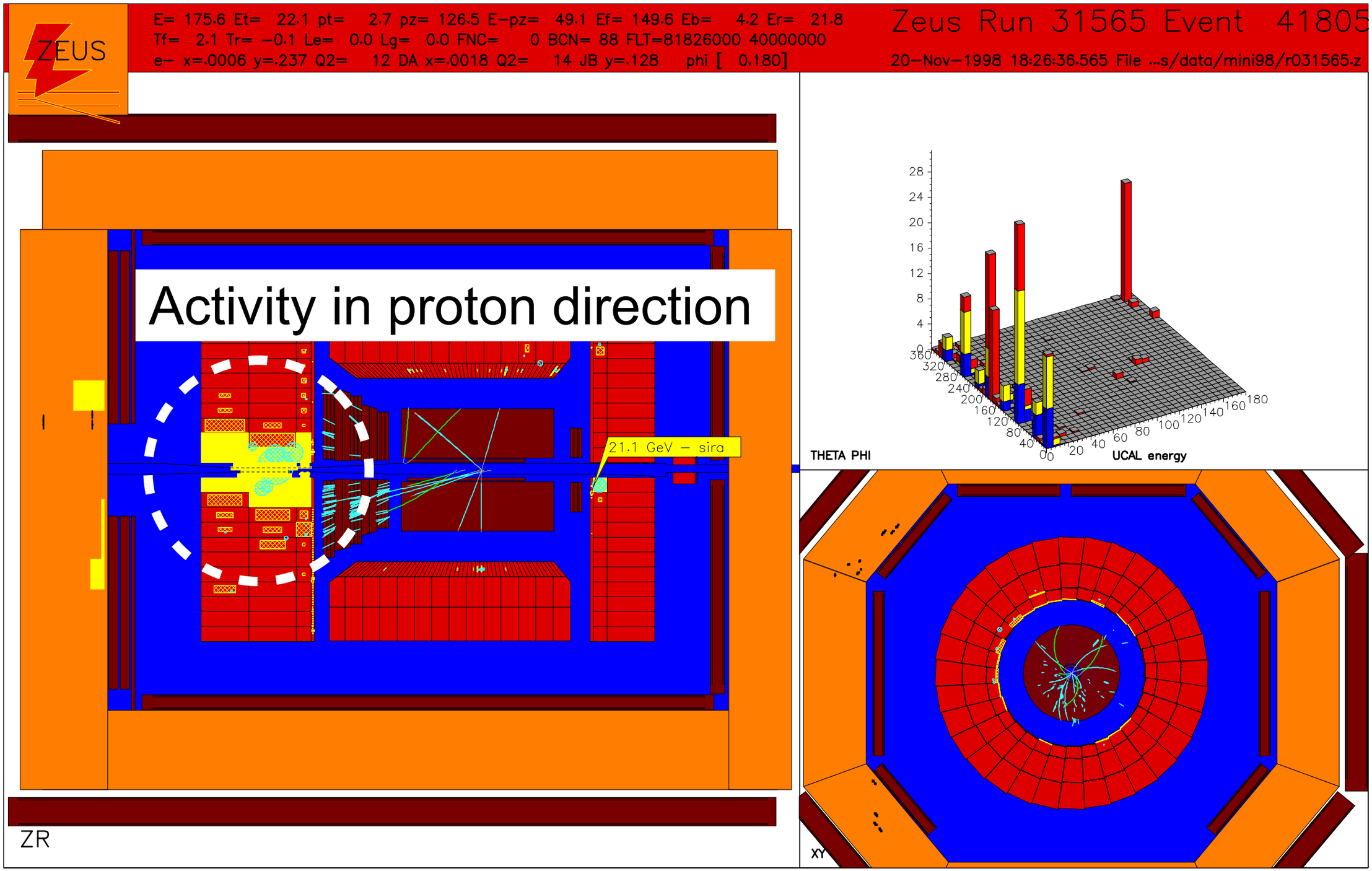
How saturated is the initial state?

What can eRHIC do?

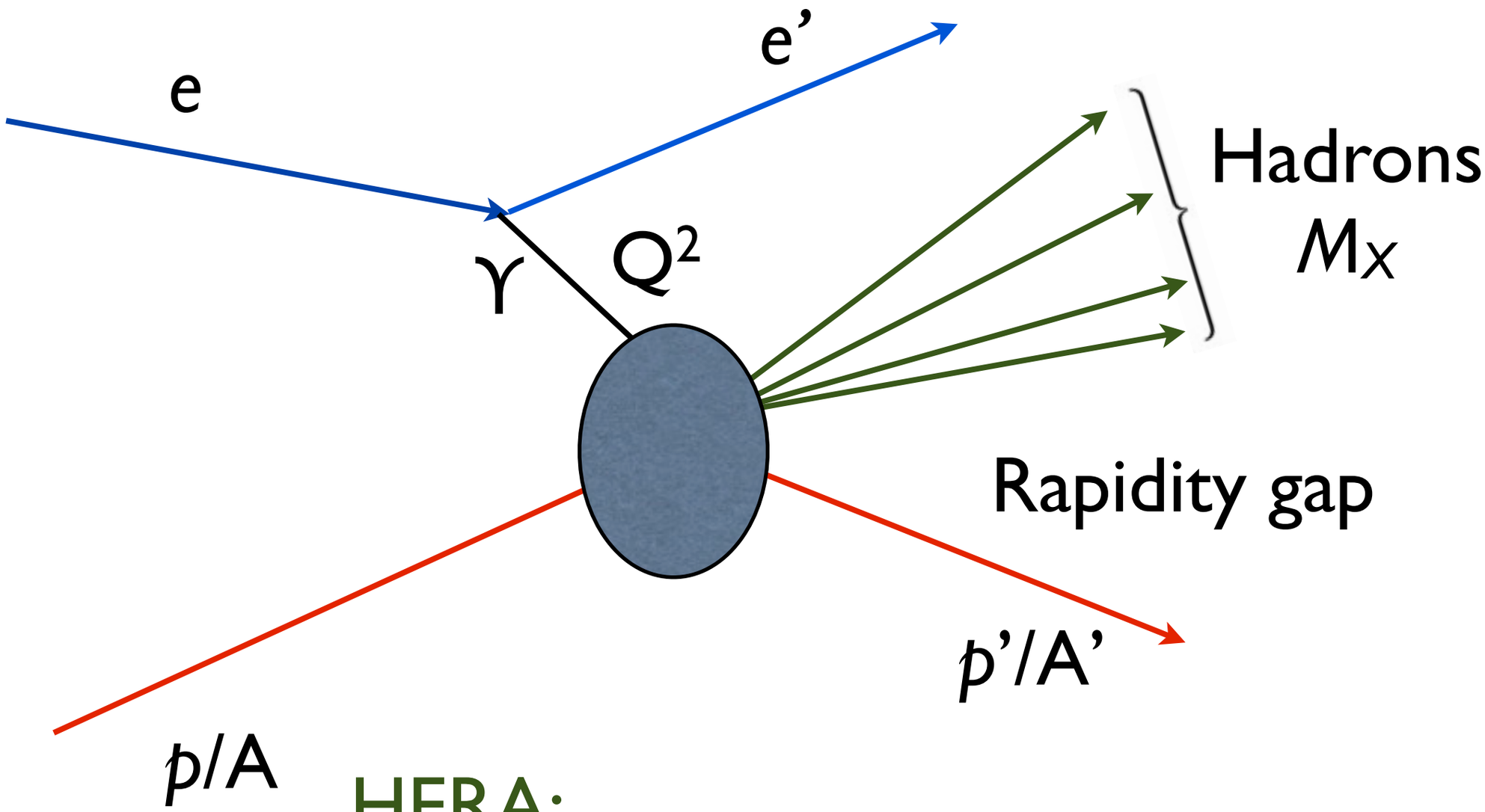
DIS *ep* and eA



DIS *ep* and eA


ZEUS
E= 175.6 Et= 22.1 pt= 2.7 pz= 126.5 E−pz= 49.1 Ef= 149.6 Eb= 4.2 Er= 21.8
Tf= 2.1 Tr= −0.1 Le= 0.0 Lg= 0.0 FNC= 0 BCN= 88 FLT=81826000 40000000
e− x=.0006 y=.237 Q2= 12 DA x=.0018 Q2= 14 JB y=.128 phi [0,180]
Zeus Run 31565 Event 41805
20−Nov−1998 18:26:36.565 File ...s/data/mini98/r031565.z
Activity in proton direction
21.1 GeV − sira
ZR
THETA PHI
UCAL energy
XY

Diffraction e*p* and eA



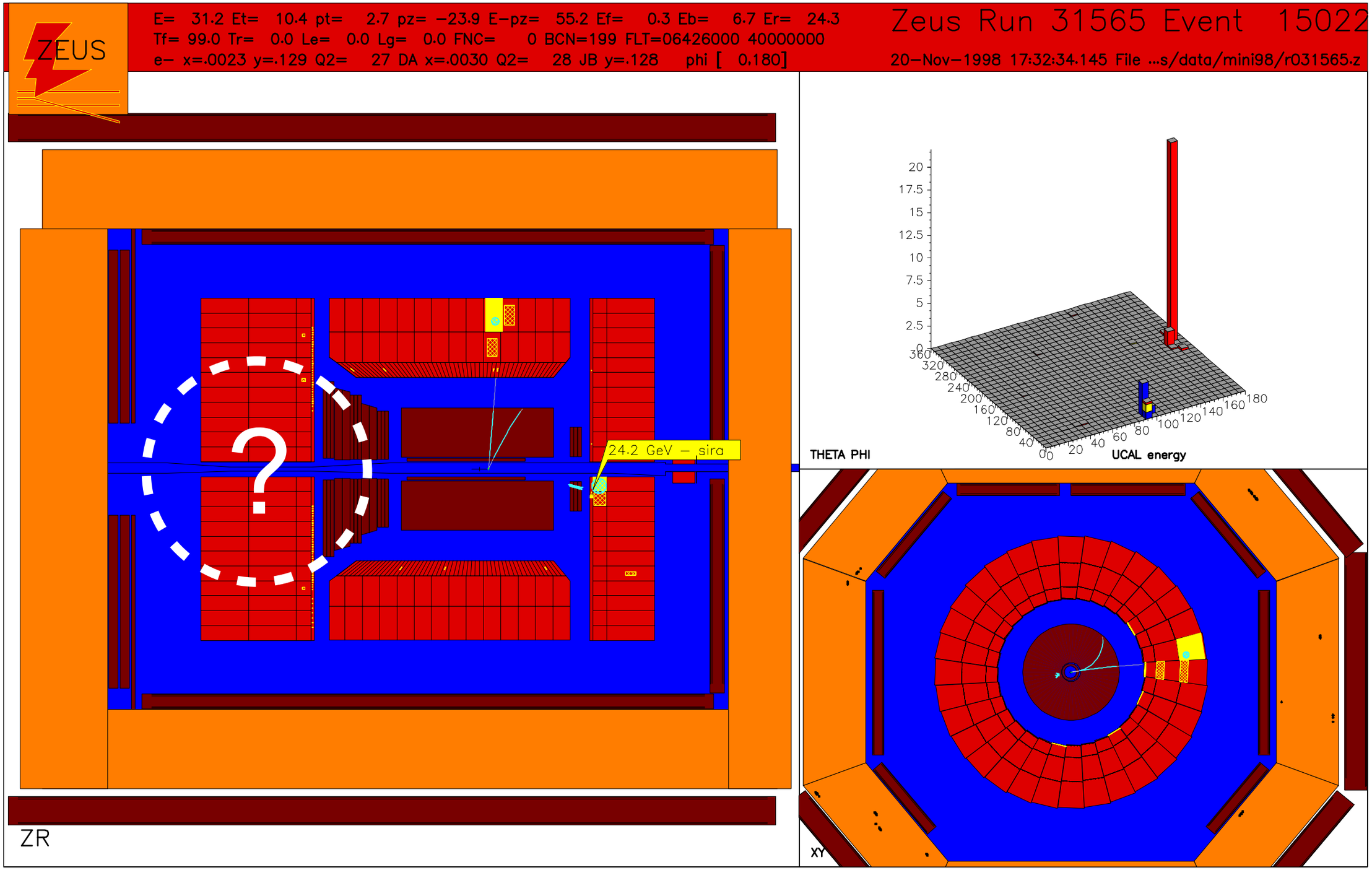
HERA:

Proton collides with electron at CMS energy ~300m_p.
In ~15% of measured collisions proton stays intact!

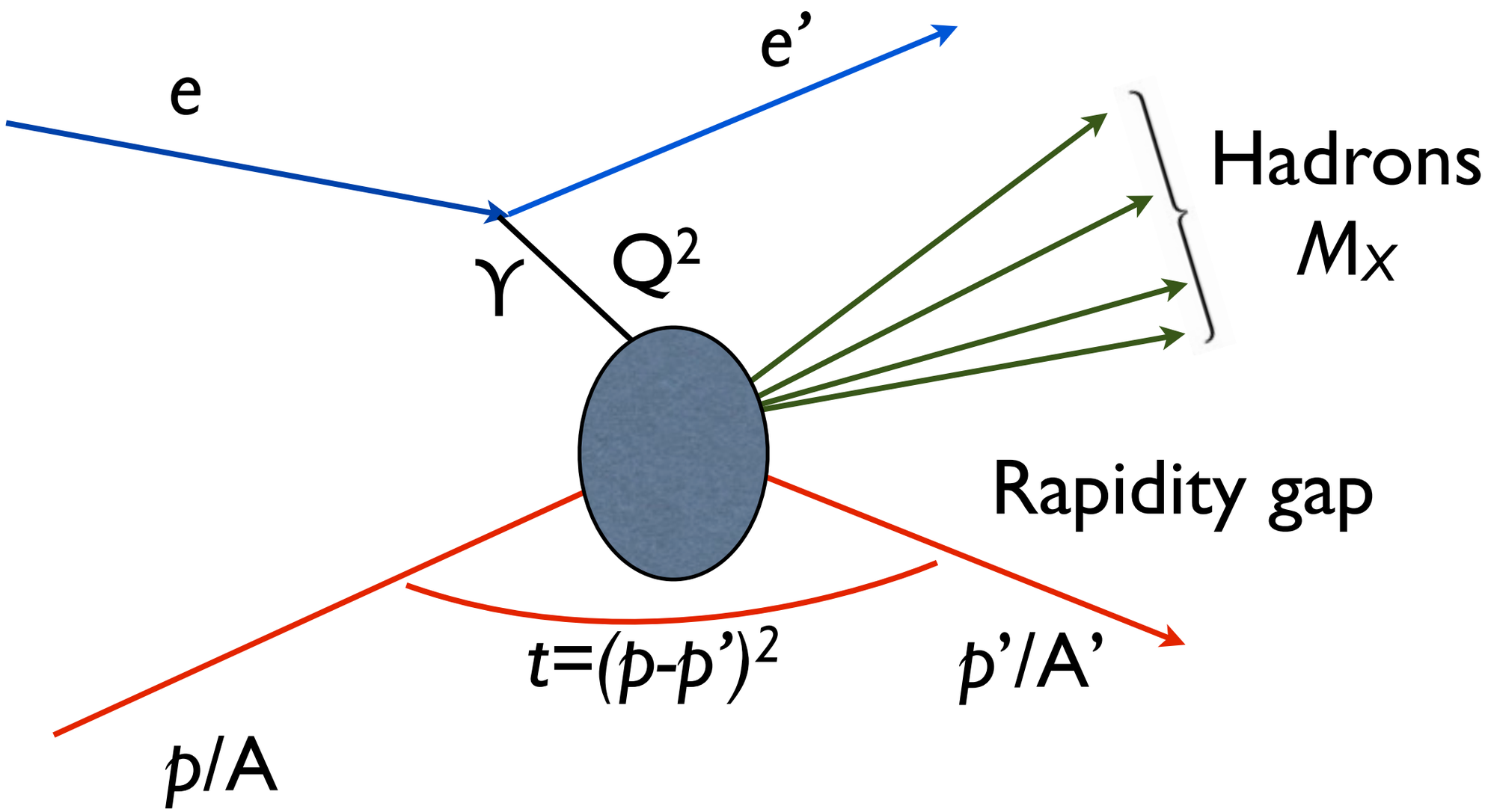
eRHIC e+A:

Ion predicted to stay intact in 25%-40% of events w. saturation!

Diffraction ep and eA



Diffraction *ep* and eA



Depend on *t*, momentum transfer to proton/ion.

Fourier transform of t-distribution

=

transverse spatial distribution

Spatial imaging!

Why is diffraction so great? Pt. 1

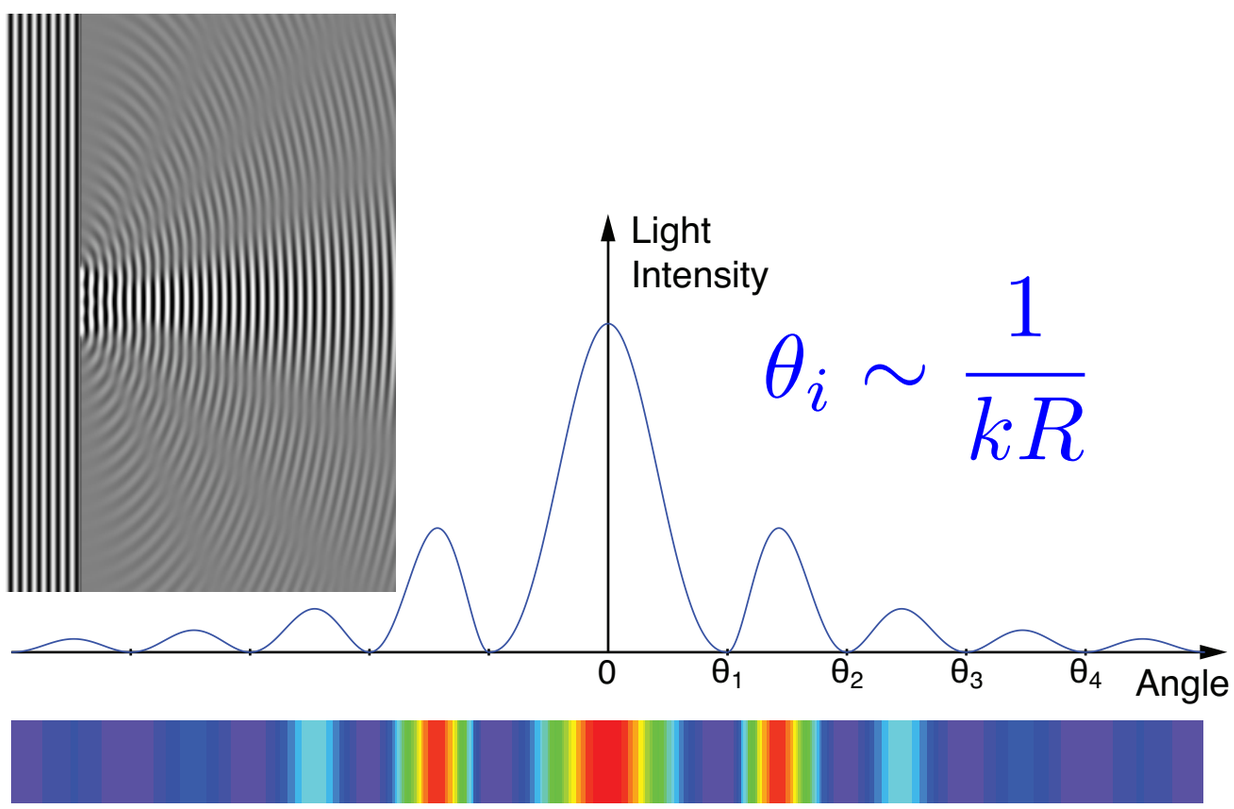
Sensitive to spatial gluon distributions

A projectile scattering off a nucleus of radius R

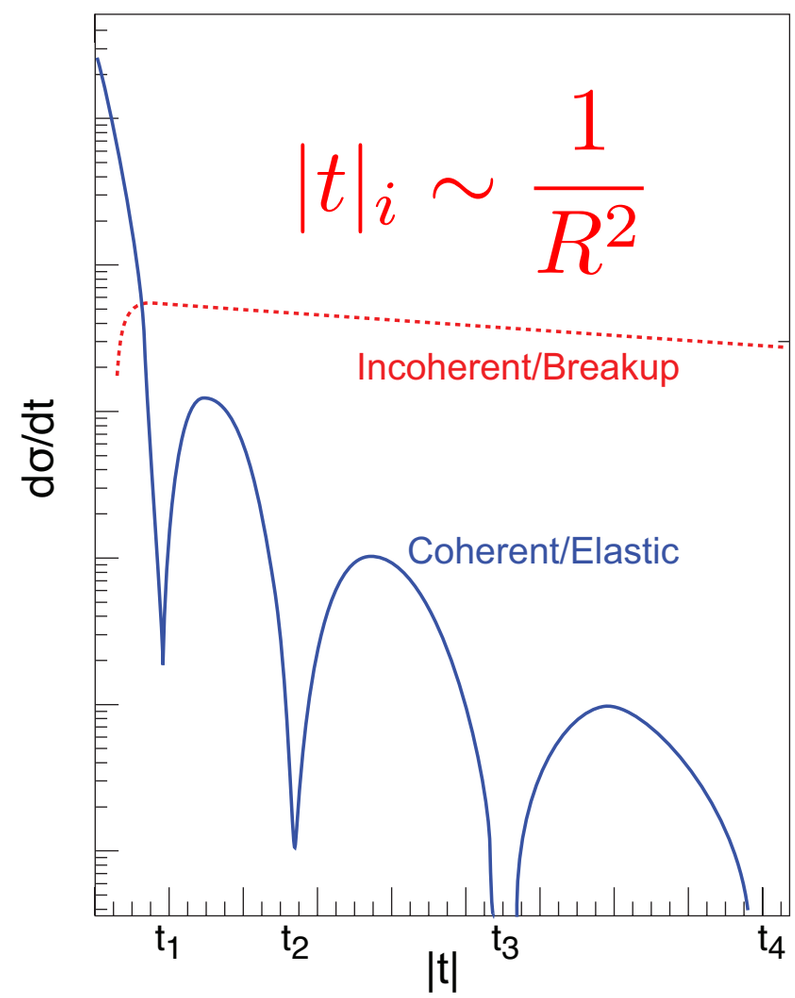
-not a 'black disk', edge effects

-target may break up

Light scattering off a circular screen of radius R



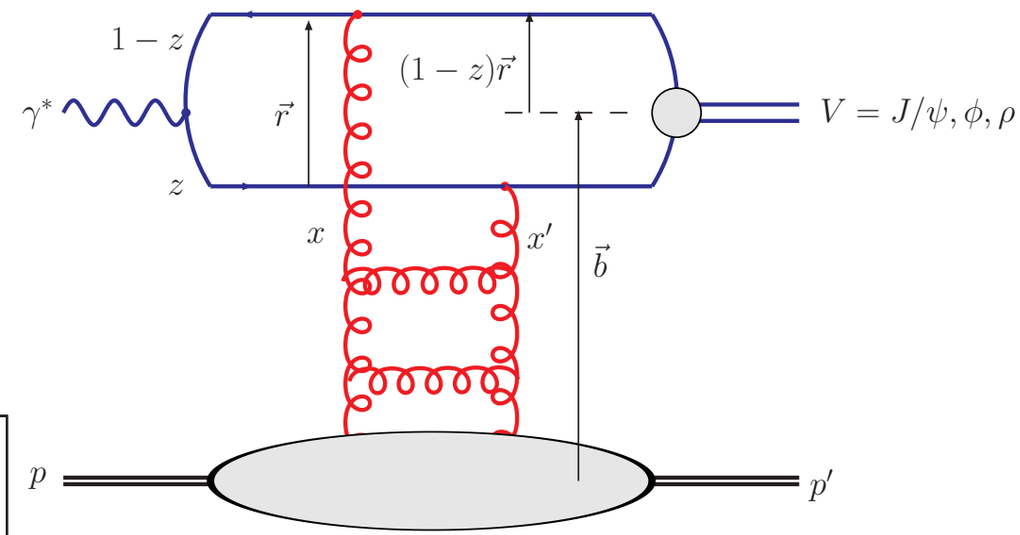
$$\theta_i \sim \frac{1}{kR}$$



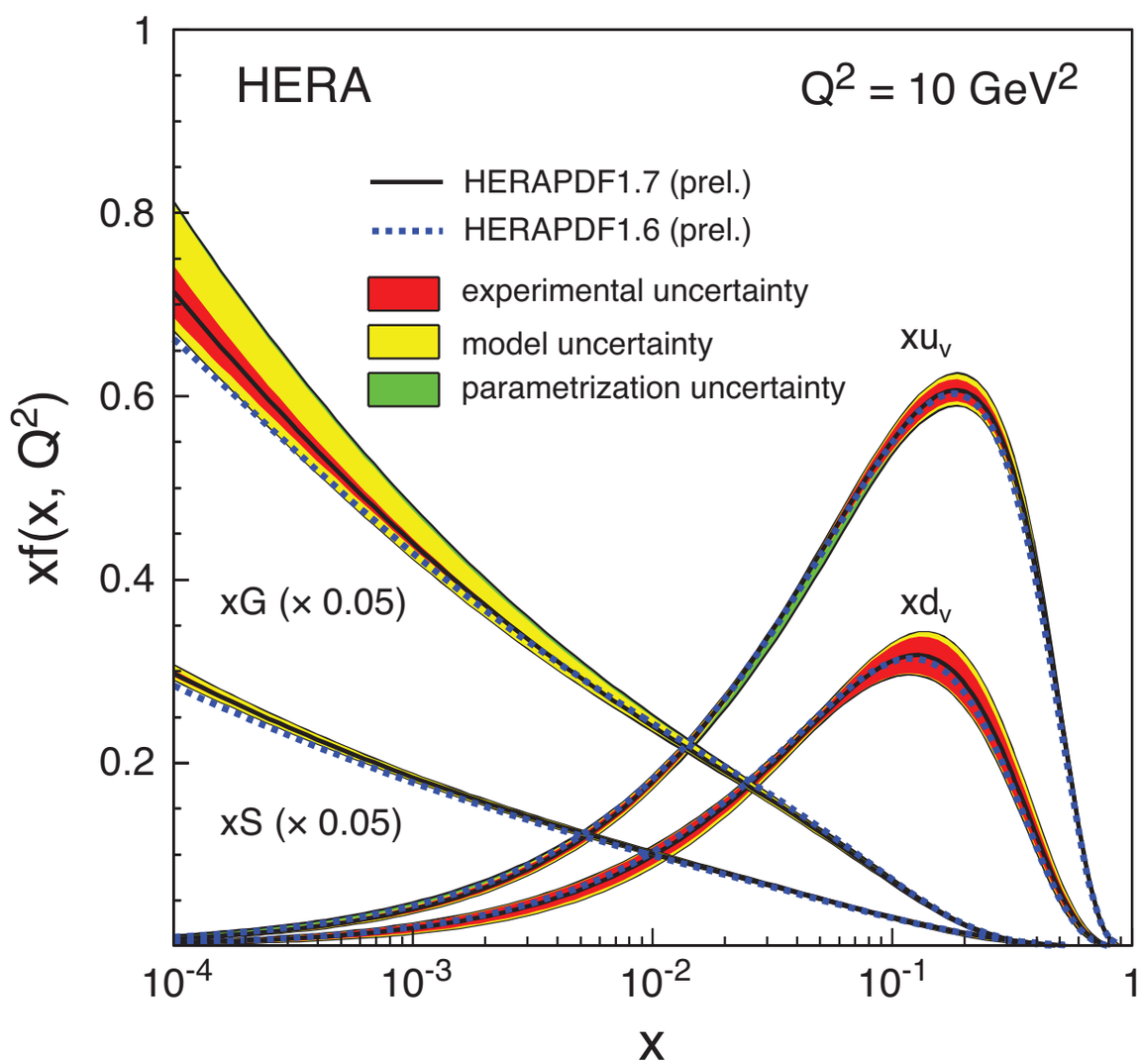
$$|t|_i \sim \frac{1}{R^2}$$

Why is diffraction so great? Pt. 2

Diffraction sensitive to gluon momentum distributions[2]:



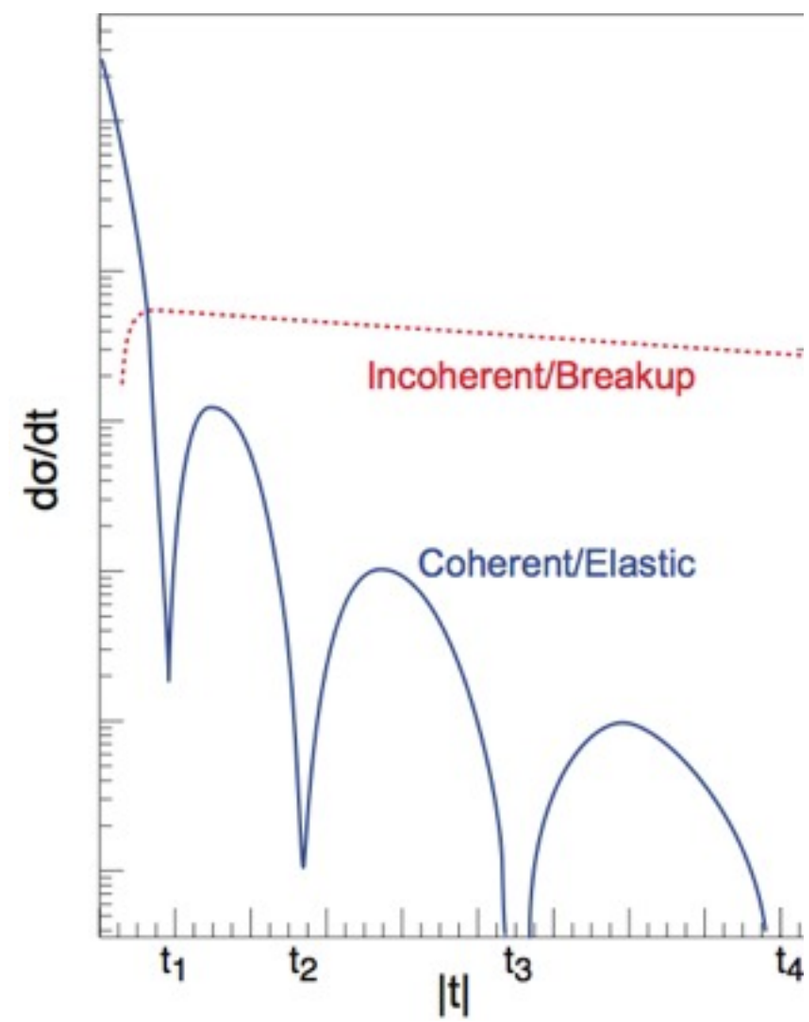
$$\sigma \propto g(x,Q^2)^2$$



How does the gluon distribution saturate at small *x*?

Diffraction at eRHIC

Difference in between *ep* & *eA*:
The nucleus can break up
into colour neutral fragments!

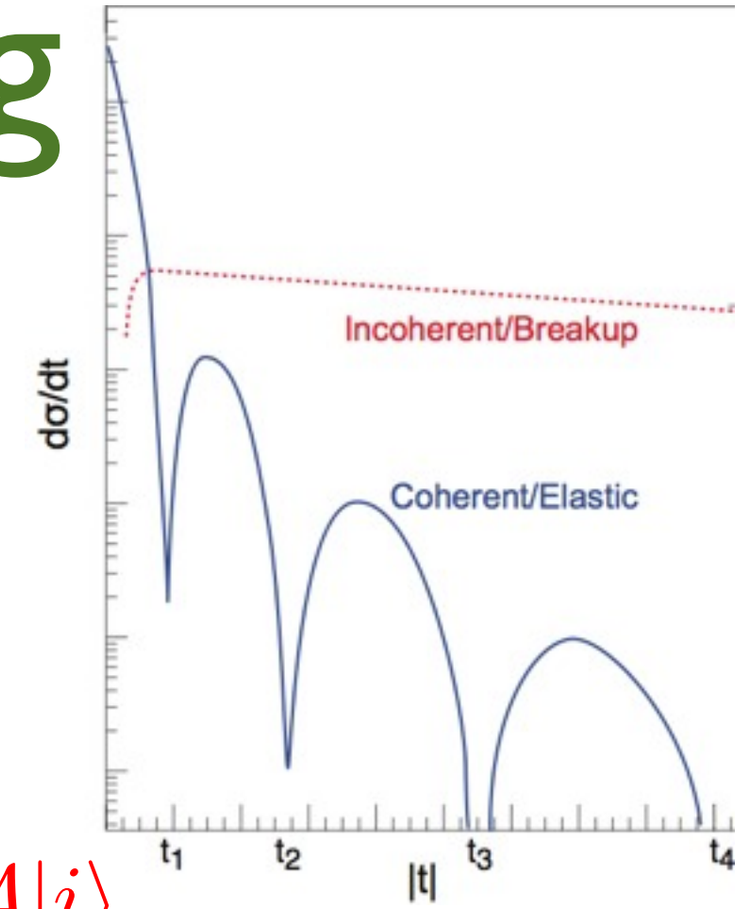


When the nucleus breaks up, the scattering is called incoherent

When the nucleus stays intact, the scattering is called coherent

Total cross-section = incoherent + coherent

Incoherent Scattering



Good, Walker:

Nucleus dissociates ($f \neq i$):

$$\sigma_{\text{incoherent}} \propto \sum_{f \neq i} \langle i|\mathcal{A}|f\rangle^\dagger \langle f|\mathcal{A}|i\rangle$$

complete set

$$= \sum_{f} \langle i|\mathcal{A}|f\rangle^\dagger \langle f|\mathcal{A}|i\rangle - \langle i|\mathcal{A}|i\rangle^\dagger \langle i|\mathcal{A}|i\rangle$$

$$= \langle i\,||\mathcal{A}|^2|\,i\rangle - |\langle i|\mathcal{A}|i\rangle|^2 = \langle |\mathcal{A}|^2\rangle - |\langle \mathcal{A}\rangle|^2$$

The incoherent CS is the variance of the amplitude!!

$$\frac{\mathrm{d}\sigma_{\text{total}}}{\mathrm{d}t} = \frac{1}{16\pi}\left\langle |\mathcal{A}|^2 \right\rangle \qquad \frac{\mathrm{d}\sigma_{\text{coherent}}}{\mathrm{d}t} = \frac{1}{16\pi}\left|\langle \mathcal{A}\rangle\right|^2$$

How to measure $t=(P_A-P_A')^2$

Need to measure $P_{A'}$

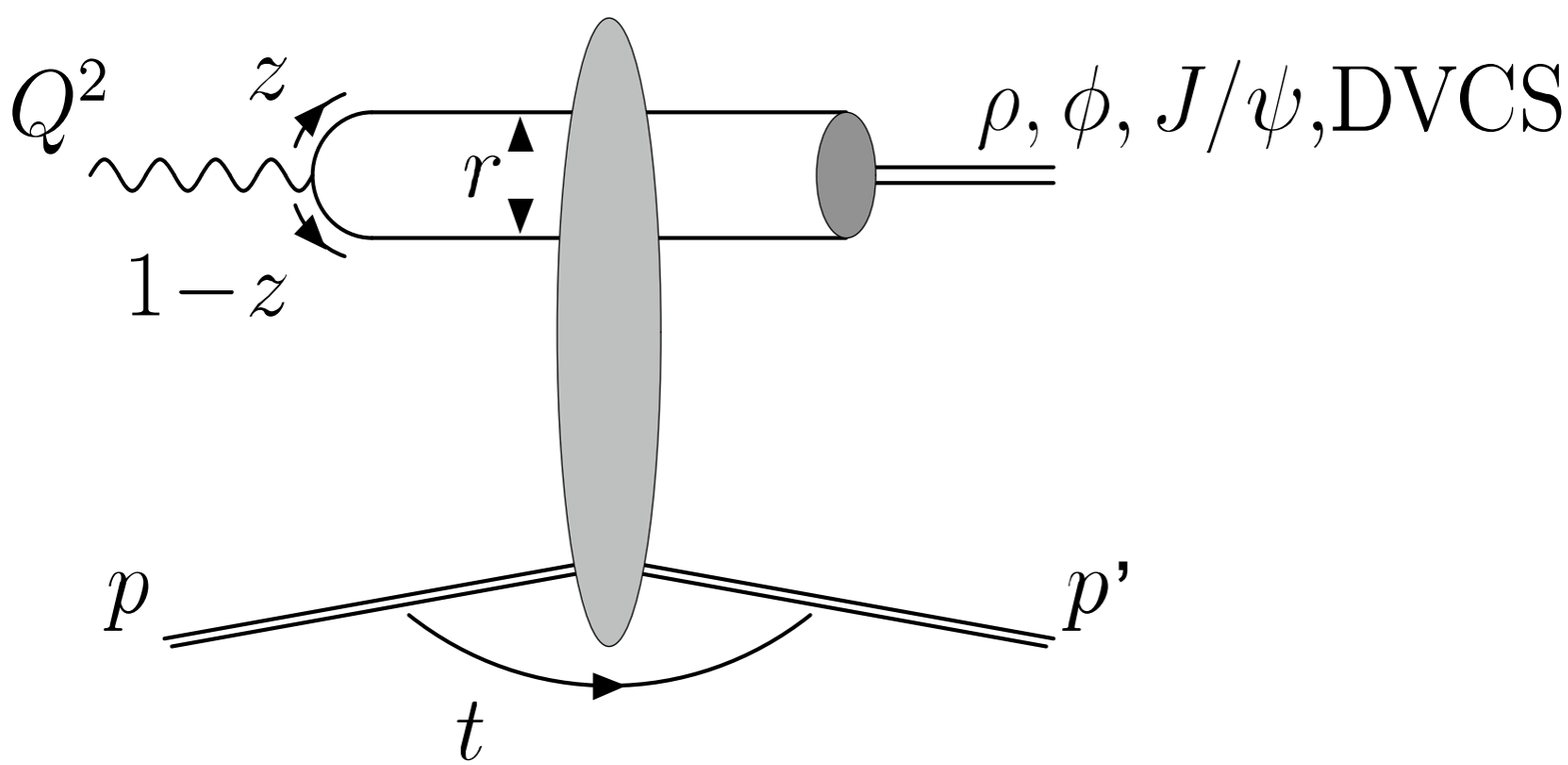
Coherent case: A' disappears down beampipe

Incoherent case: Cannot measure all beam remnants

Only possibility: Exclusive diffraction

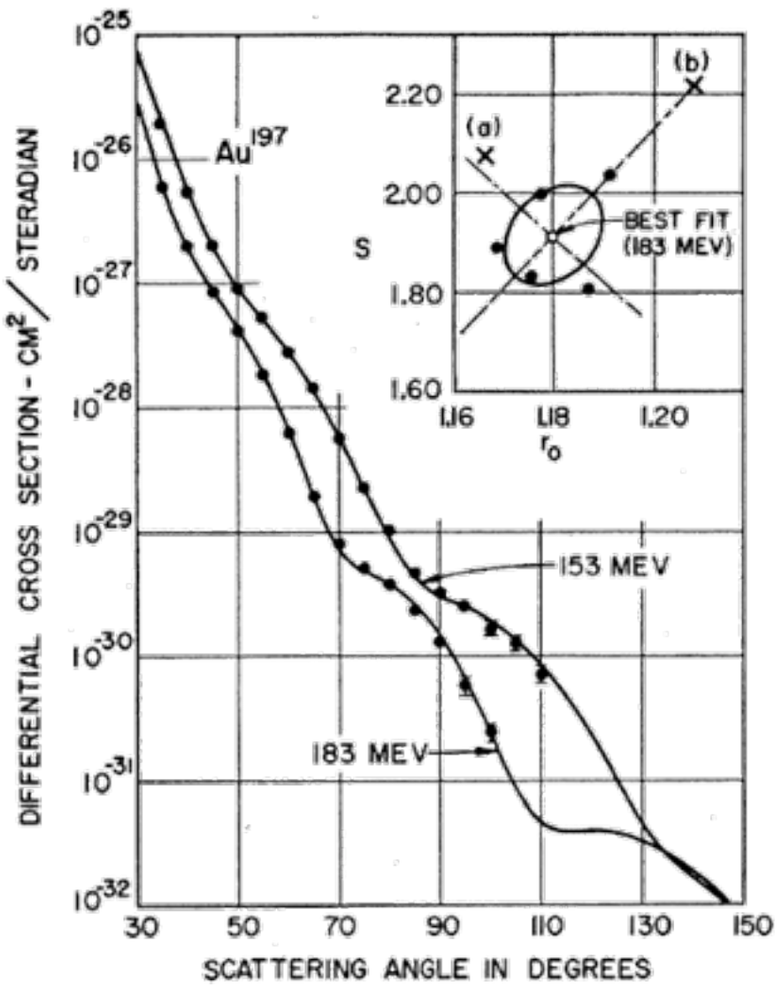
$e+A \rightarrow e'+VM+A'$

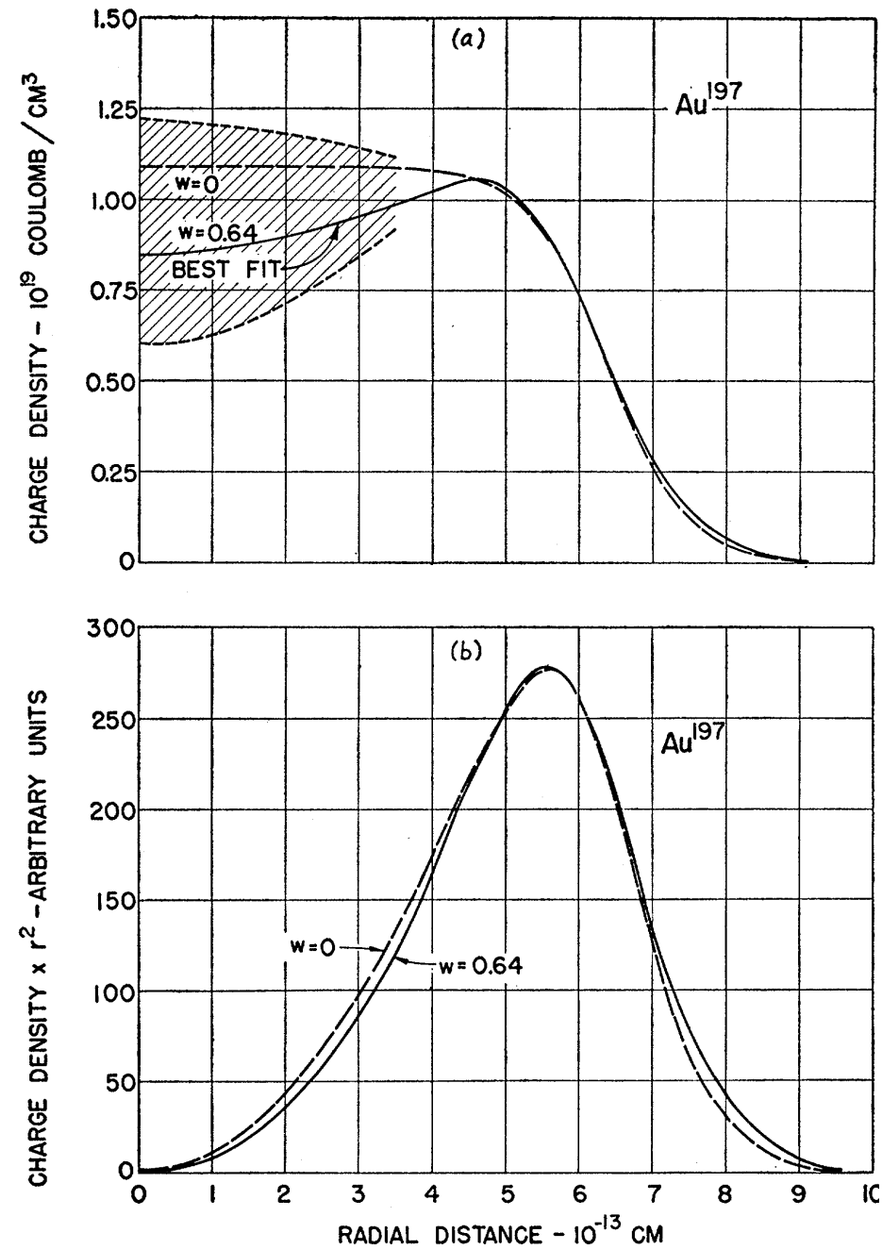
$t=(P_{VM}+P_{e'}-P_e)^2$



What has been measured?

Hahn, Ravenhall, and Hofstadter,
Phys Rev 101 (1956)



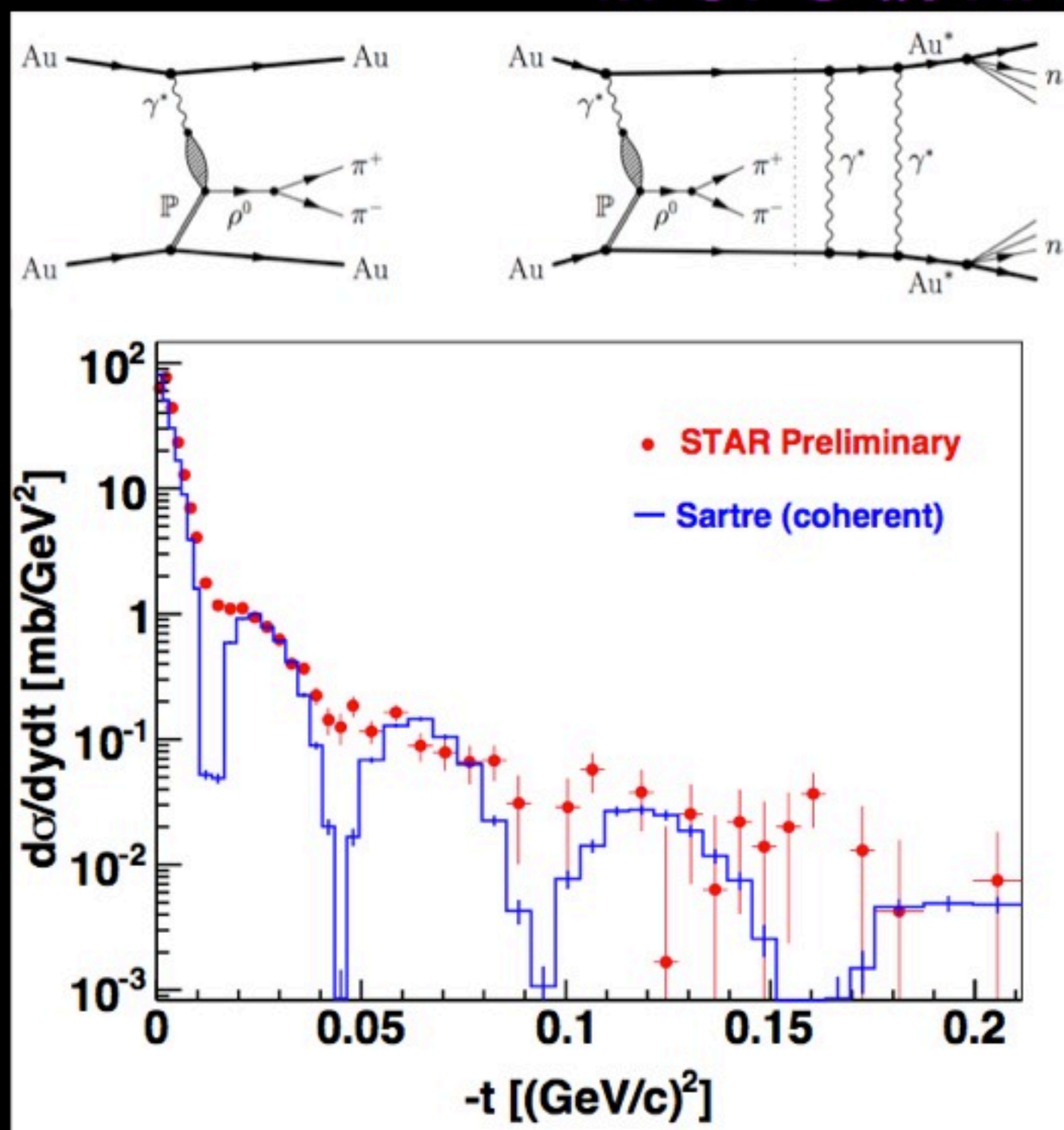


Electron colliding with fixed ion target,
large *x* charge distribution - no gluons!

What is being measured?

Slide from J.H. Lee,
Analysis: R. Debbe

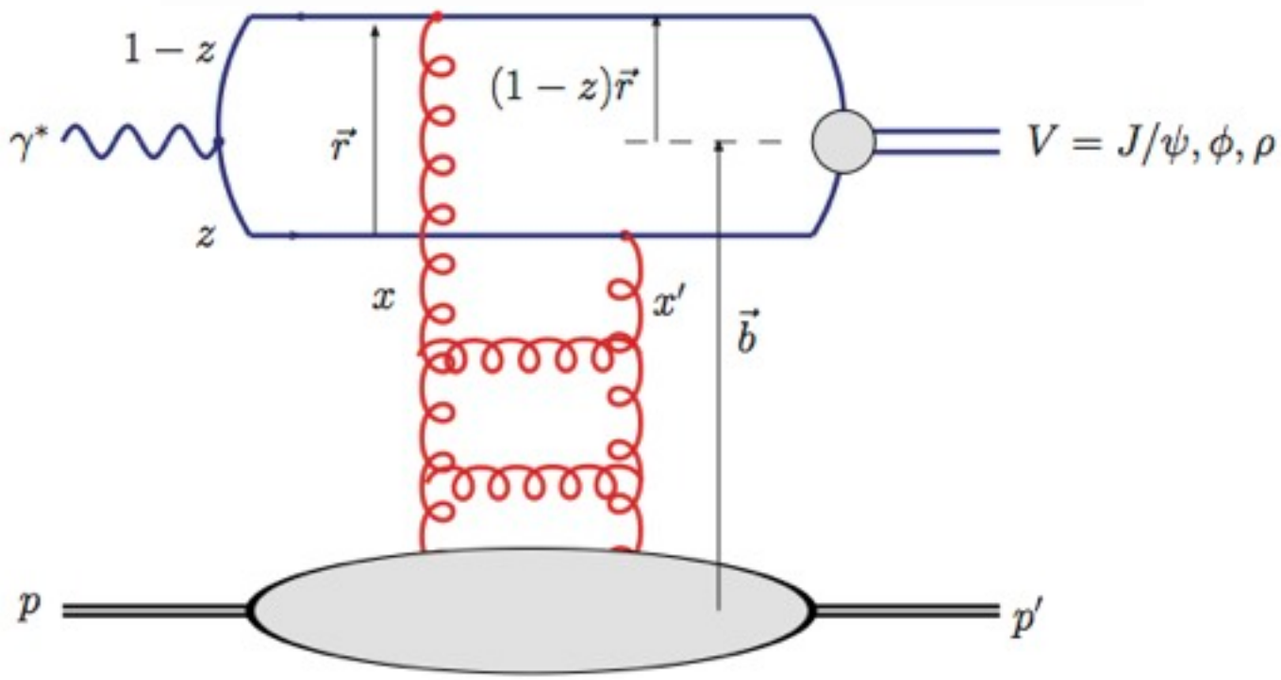
Coherent Diffraction (γ^*+IP) in UPC at RHIC



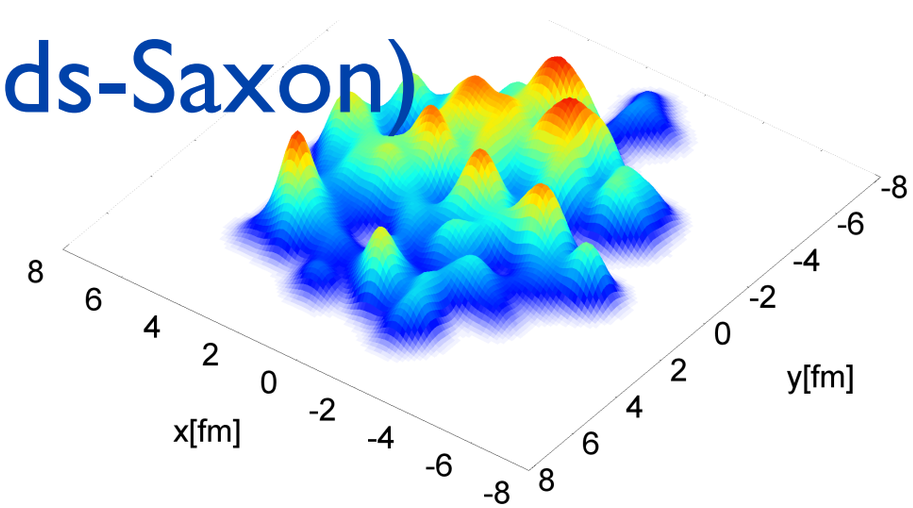
- Coherent diffractive ρ production in Au +Au at $\sqrt{s_{NN}}$=200 GeV
- Data: STAR/RHIC Ultra-peripheral AuAu Collision
- Simulation: Sartre

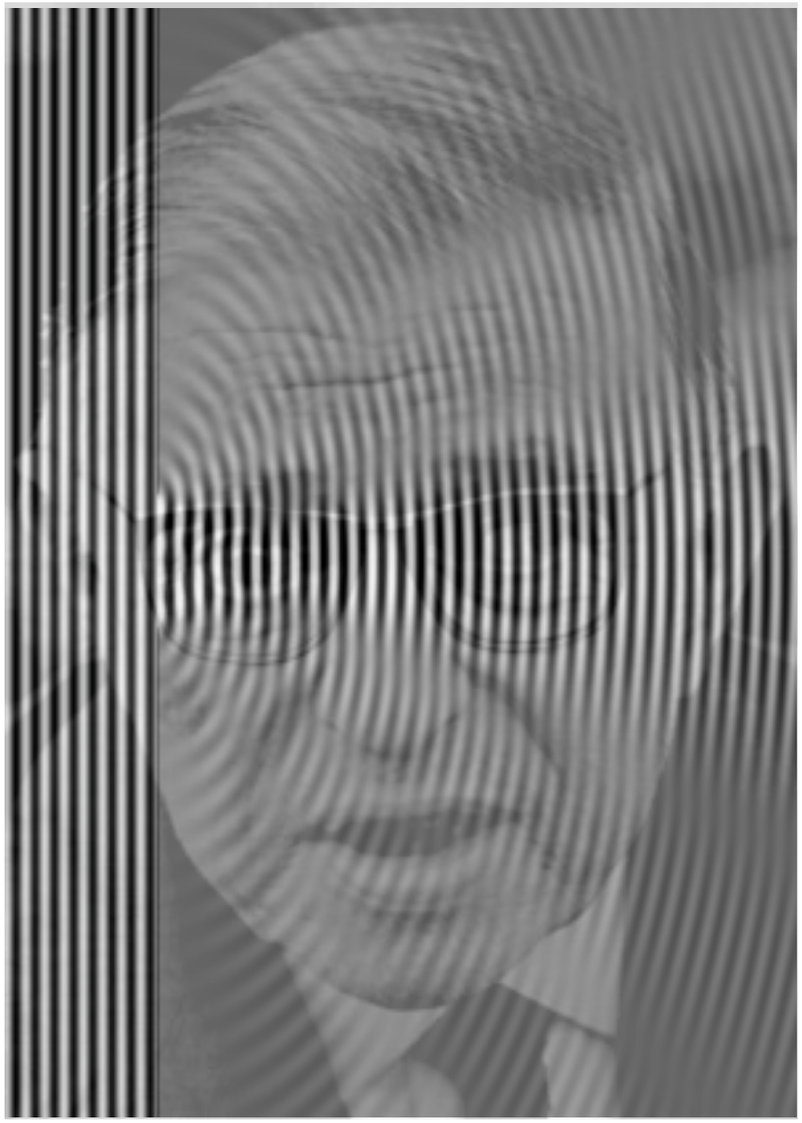
No t-smearing in Sartre

eRHIC predictions: Exclusive diffraction Sartre



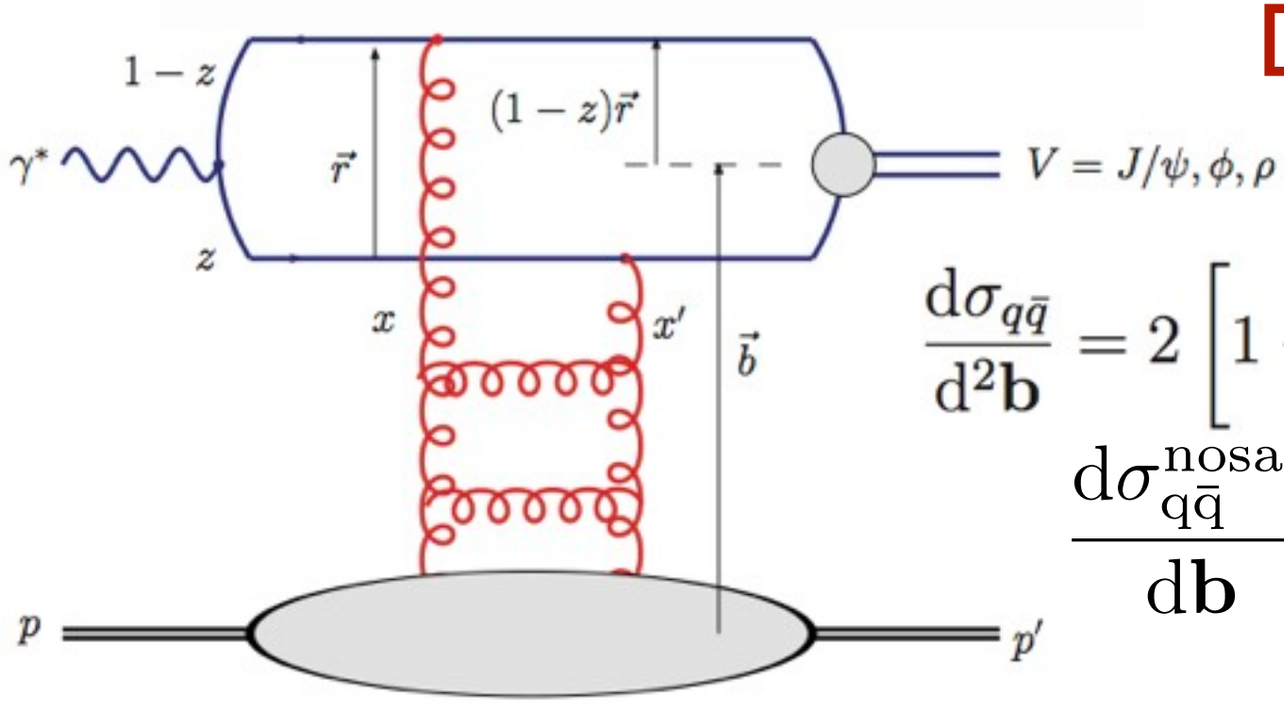
Glauber (Woods-Saxon)





T. Ullrich & T.T.

eRHIC predictions: Exclusive diffraction Sartre



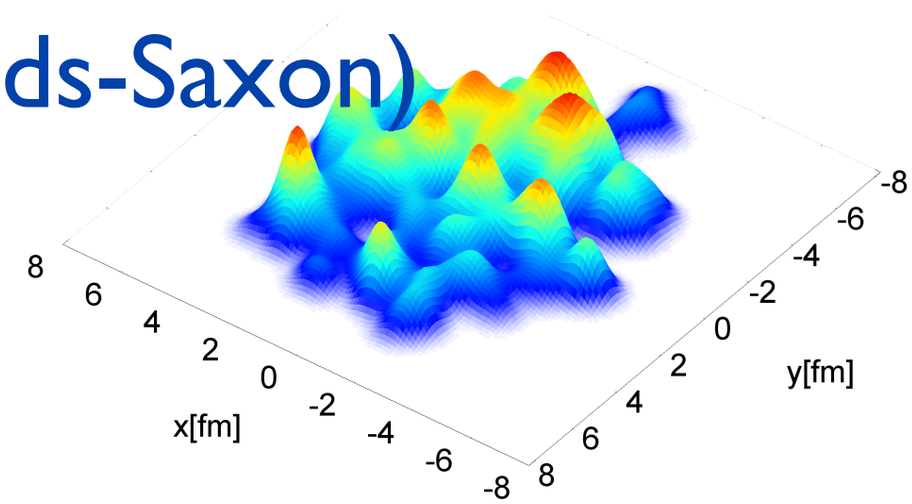
Dipole model with Glauber

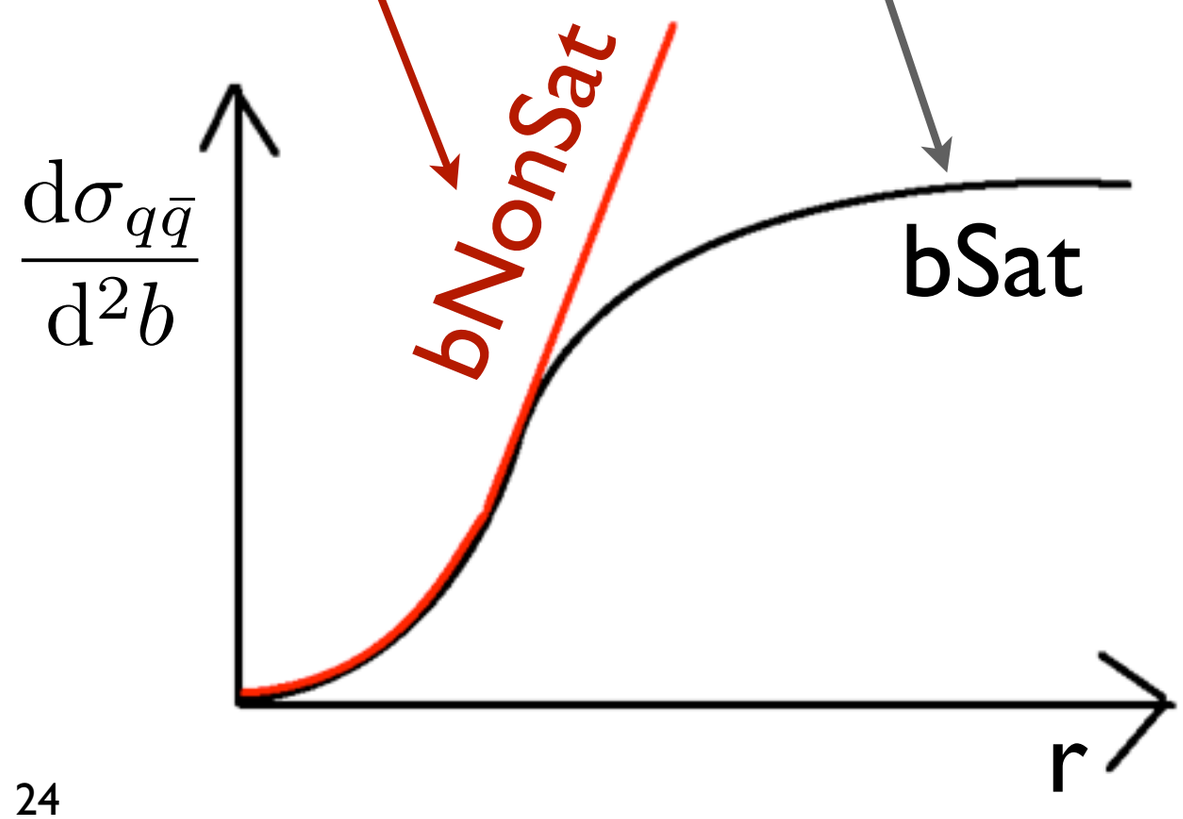
bSat and bNonSat

$$\frac{d\sigma_{q\bar{q}}}{d^2\mathbf{b}} = 2\left[1 - \exp\left(-\frac{\pi^2}{2N_c} r^2 \alpha_s(\mu^2) x g(x, \mu^2) T(b)\right)\right]$$

$$\frac{d\sigma_{q\bar{q}}^{nosat}}{d\mathbf{b}} = \frac{\pi^2}{N_C} r^2 \alpha_S(\mu^2) x g(x, \mu^2) T(b)$$

Glauber (Woods-Saxon)



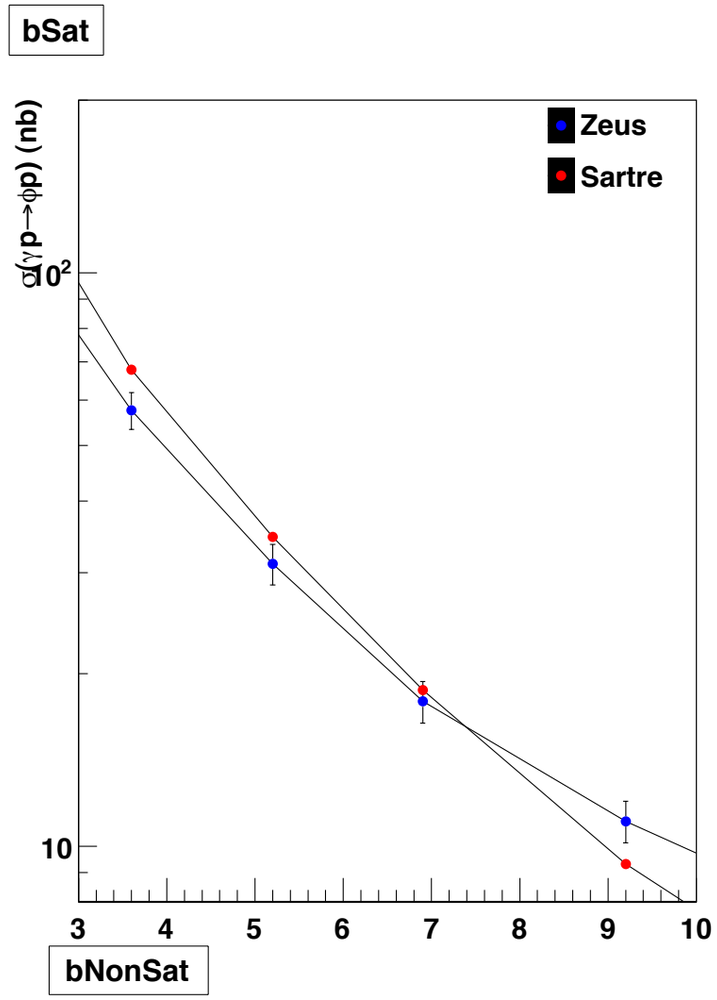


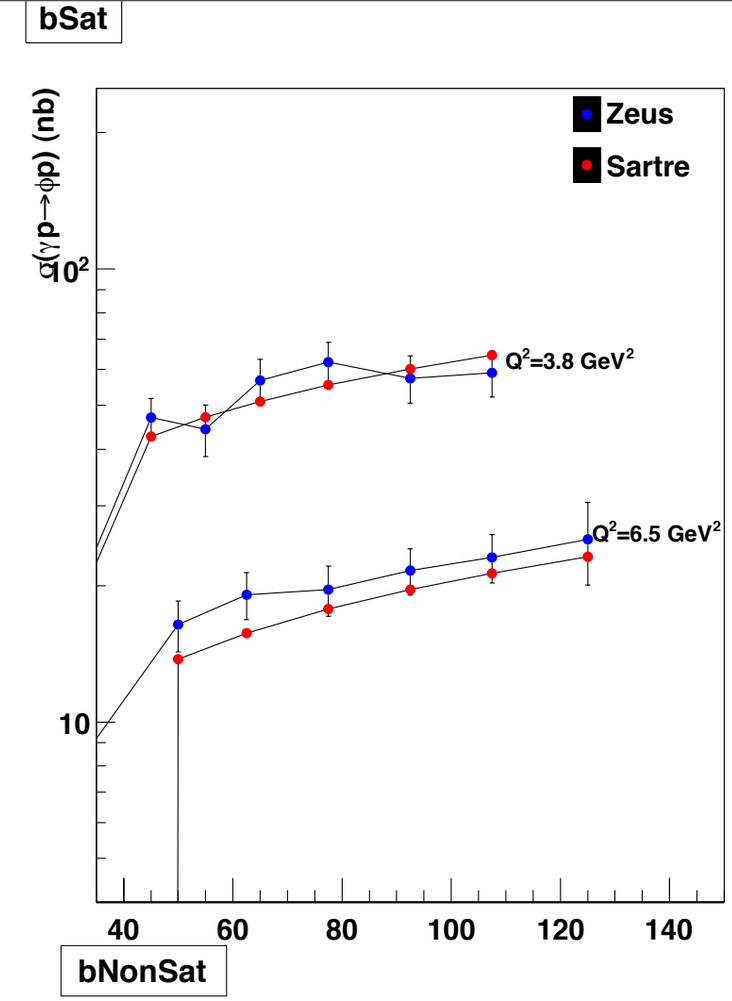
bSat vs. bNonSat at HERA

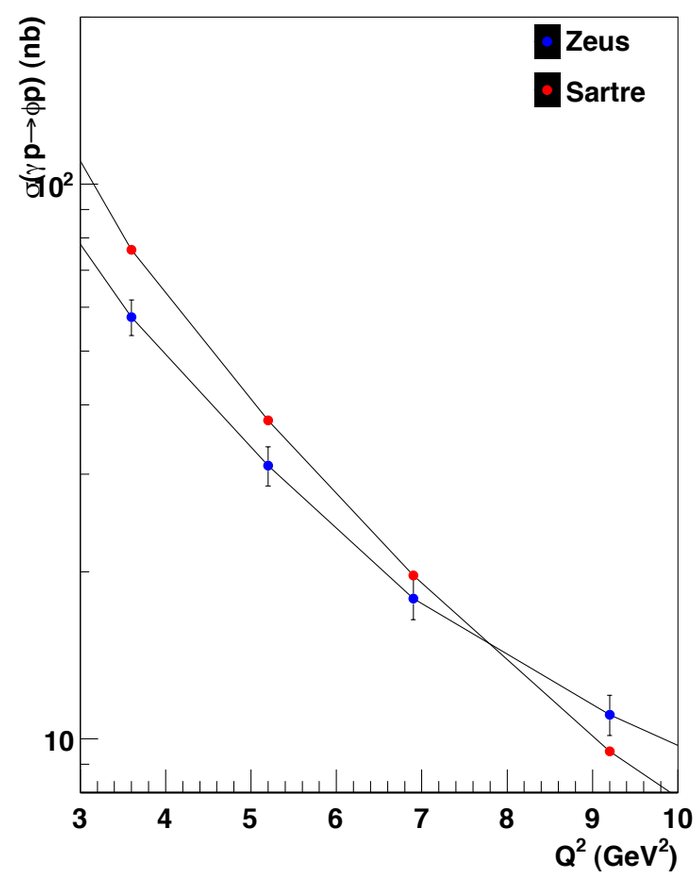
ϕ – mesons

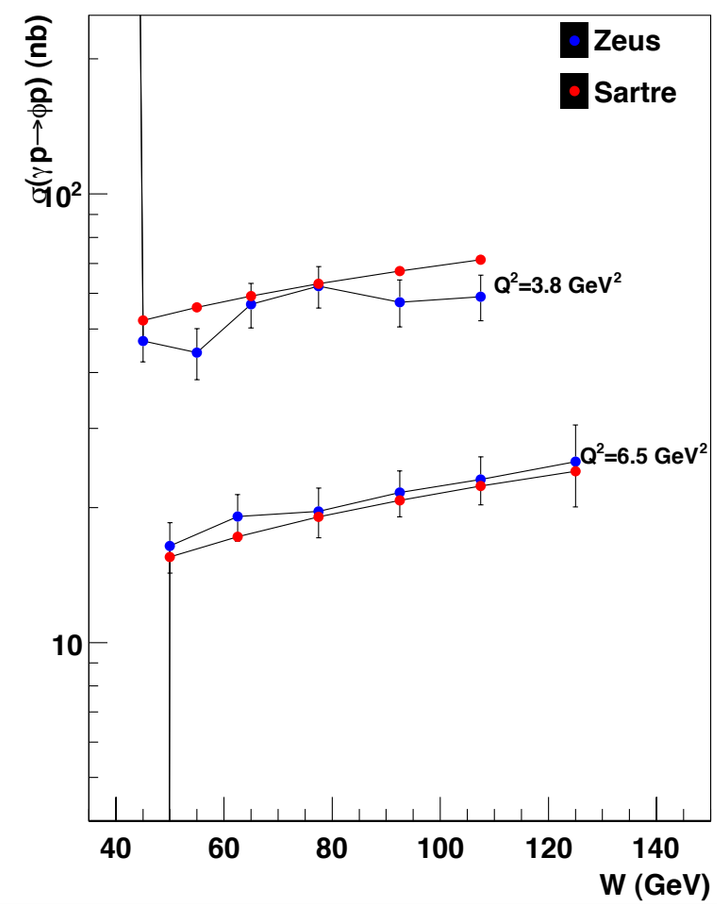
No distinguishing power!

eRHIC can probe the difference!

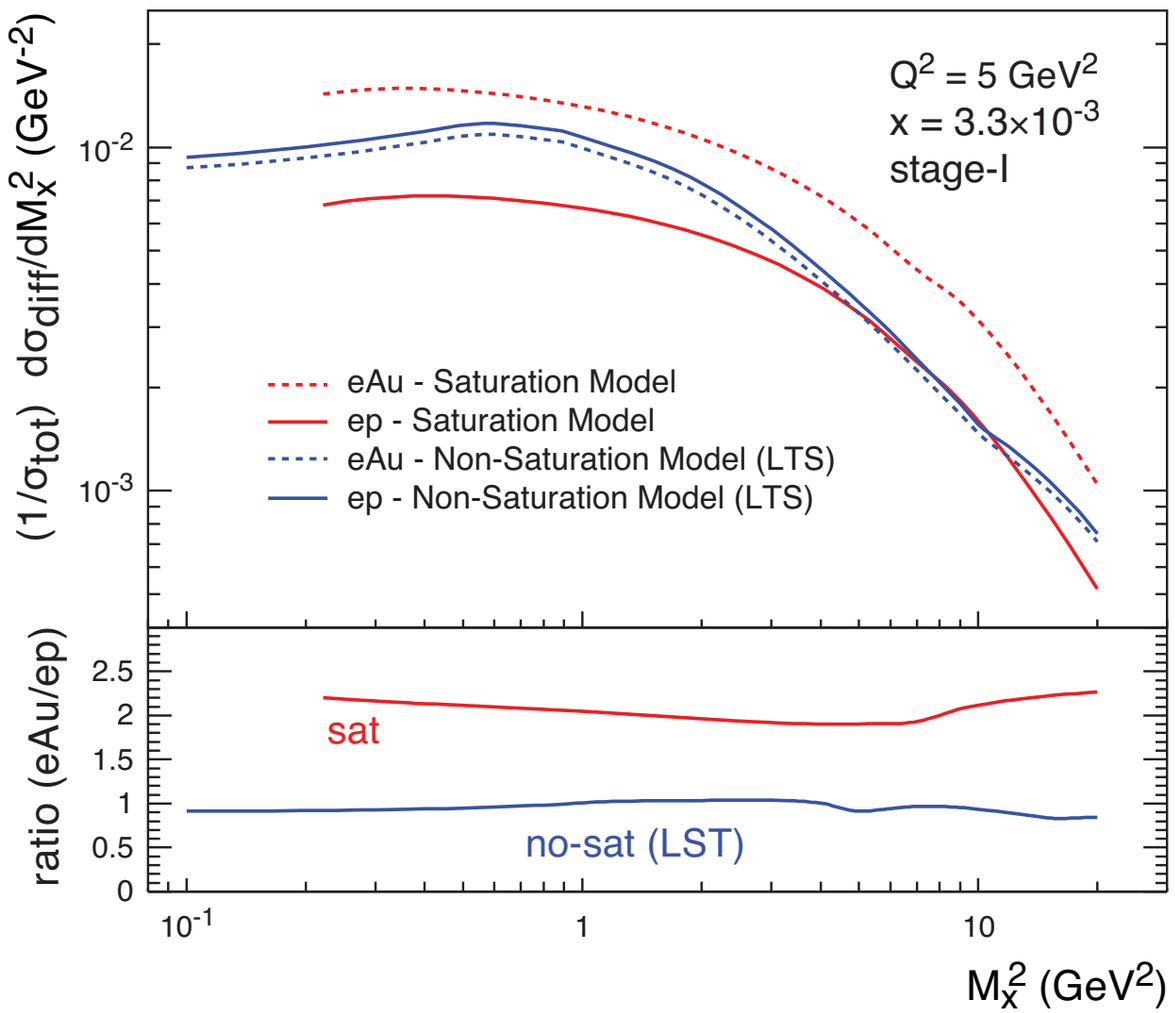


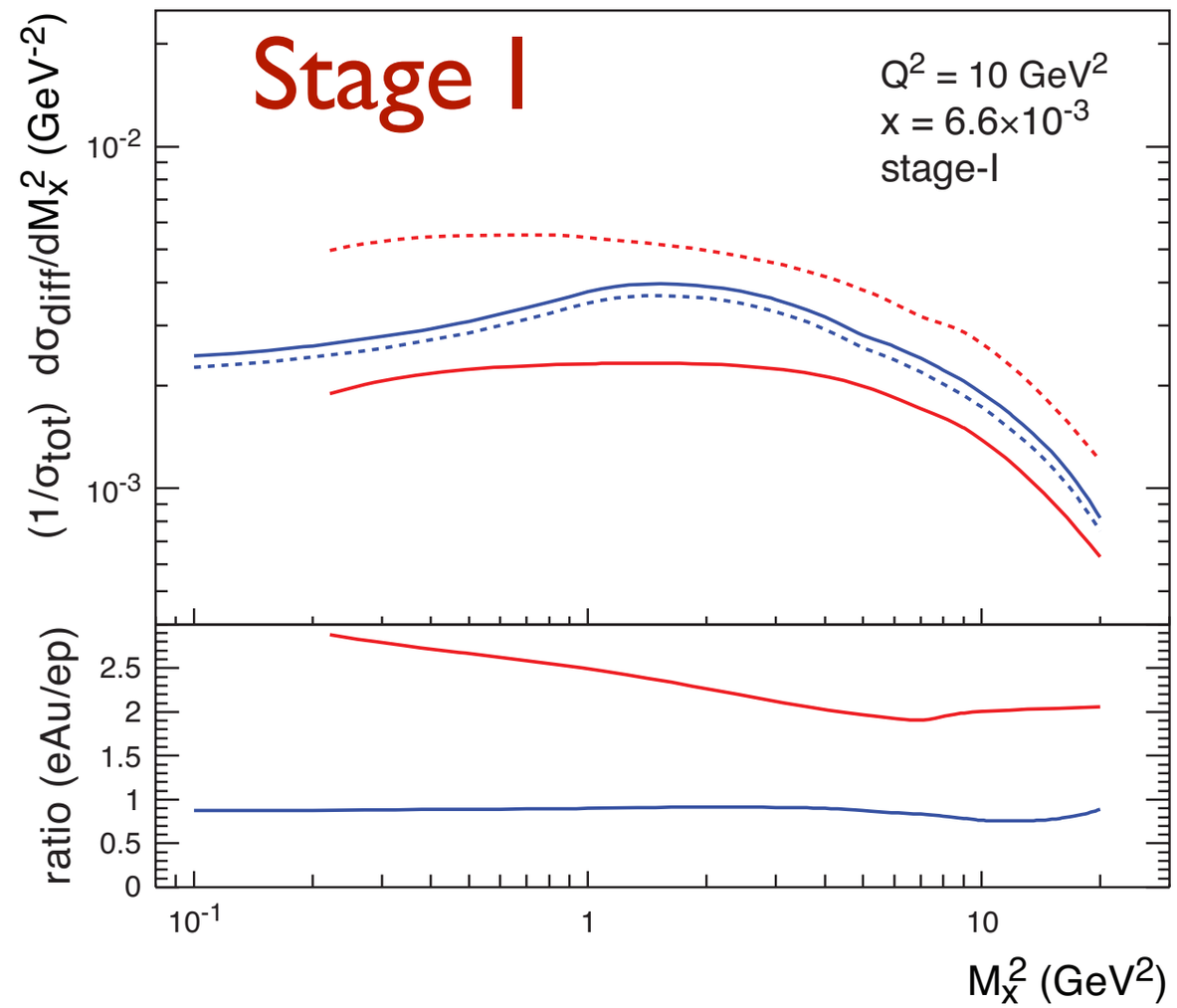






eRHIC predictions: Inclusive diffraction





Can constrain models a lot with a few months of running!
Already in Stage I!

Probing the spatial gluon distribution at eRHIC

Amplitude is a Fourier transform from position to momentum space:

$$\left\langle \mathcal{A}_{T,L}(Q^2, \Delta, x_{I\!P}) \right\rangle_\Omega = \int \pi r \mathrm{d}r \mathrm{d}z b \mathrm{d}b (\Psi_V^* \Psi)_{T,L} (Q^2, r, z)$$

$$J_0([1-z]r\Delta) J_0(b\Delta) \left\langle \frac{\mathrm{d}\sigma_{q\bar{q}}}{\mathrm{d}^2\mathbf{b}} \right\rangle_\Omega (x_{I\!P}, r, b)$$

Cross-section:

$$\frac{\mathrm{d}\sigma}{\mathrm{d}t} = \frac{1}{16\pi} \left| \left\langle \mathcal{A}_{T,L}(Q^2, \Delta, x_{I\!P}) \right\rangle_\Omega \right|^2$$

Fourier transform again to retain spatial distribution:

$$F(b) = \frac{1}{2\pi} \int_0^\infty \mathrm{d}\Delta \Delta J_0(\Delta b) \sqrt{\frac{\mathrm{d}\sigma_{\mathrm{coherent}}}{\mathrm{d}t}(\Delta)} \Bigg|_{\mathrm{mod}}$$

Probing the spatial gluon distribution at eRHIC

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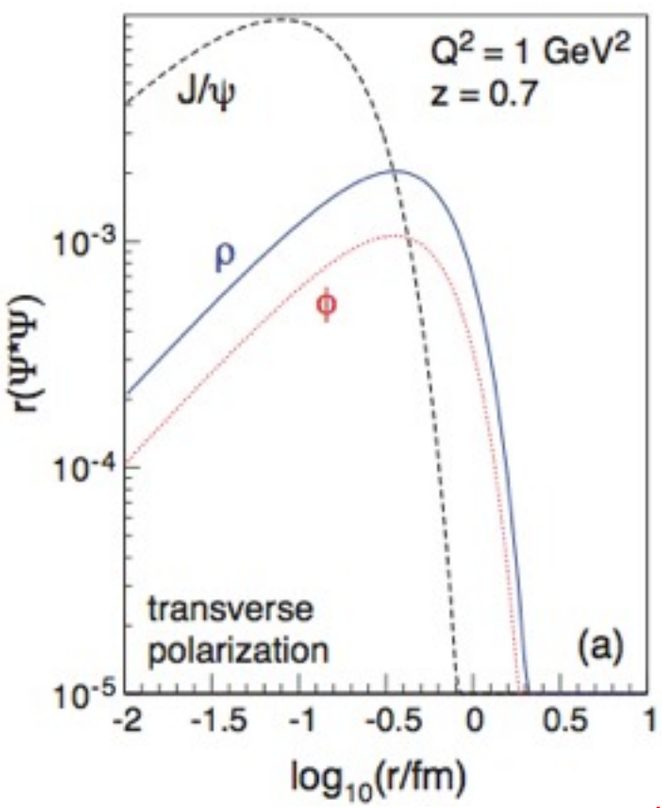
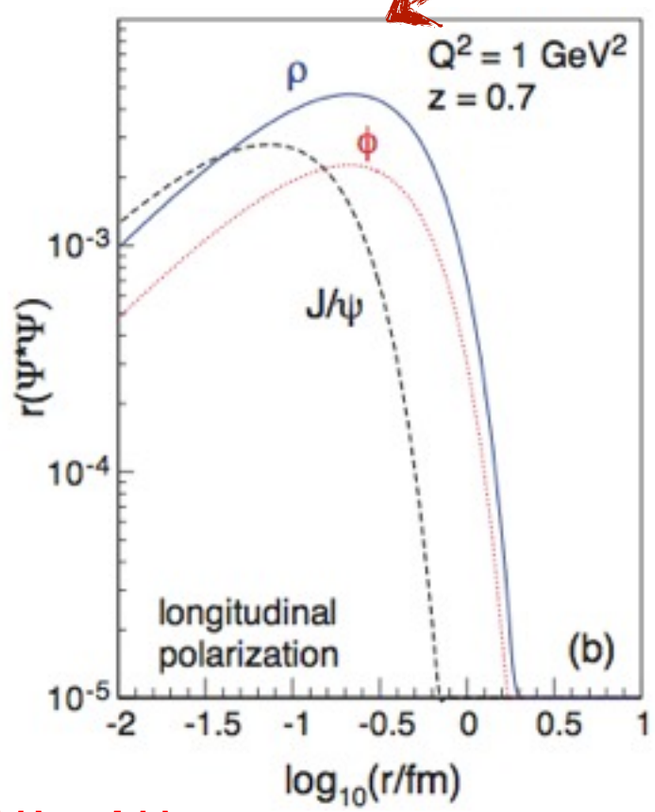
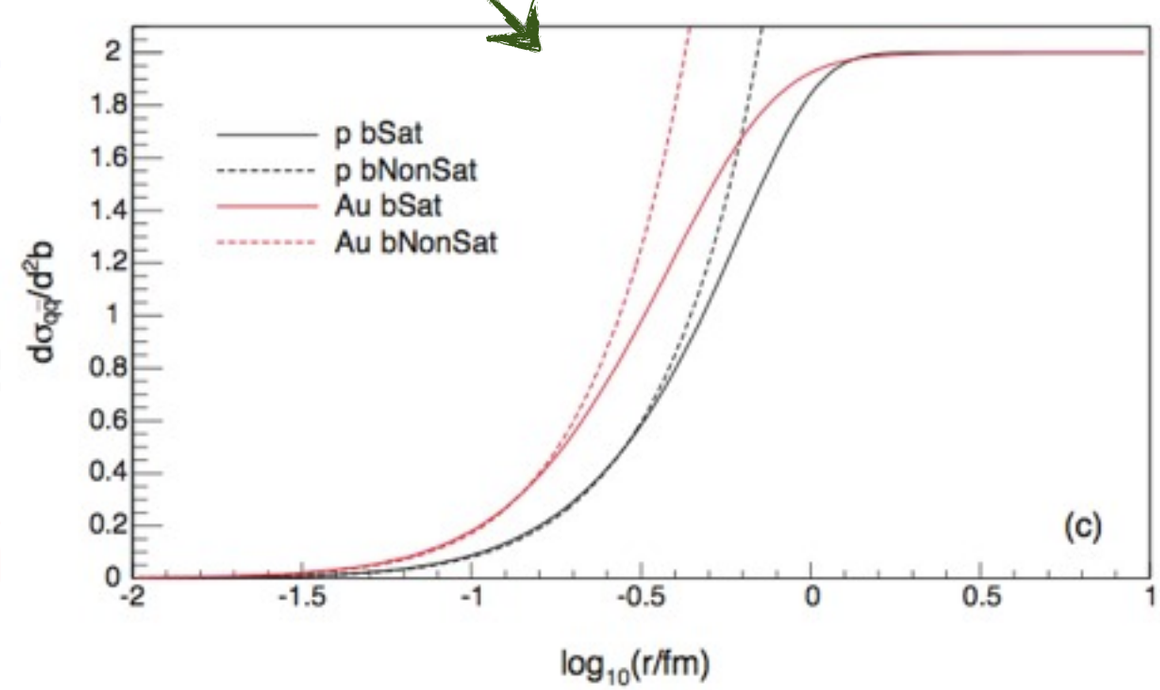
$$J_0([1-z]r\Delta) J_0(b\Delta) \left\langle \frac{\mathrm{d}\sigma_{q\bar{q}}}{\mathrm{d}^2\mathbf{b}} \right\rangle_\Omega (x_{I\!P}, r, b)$$

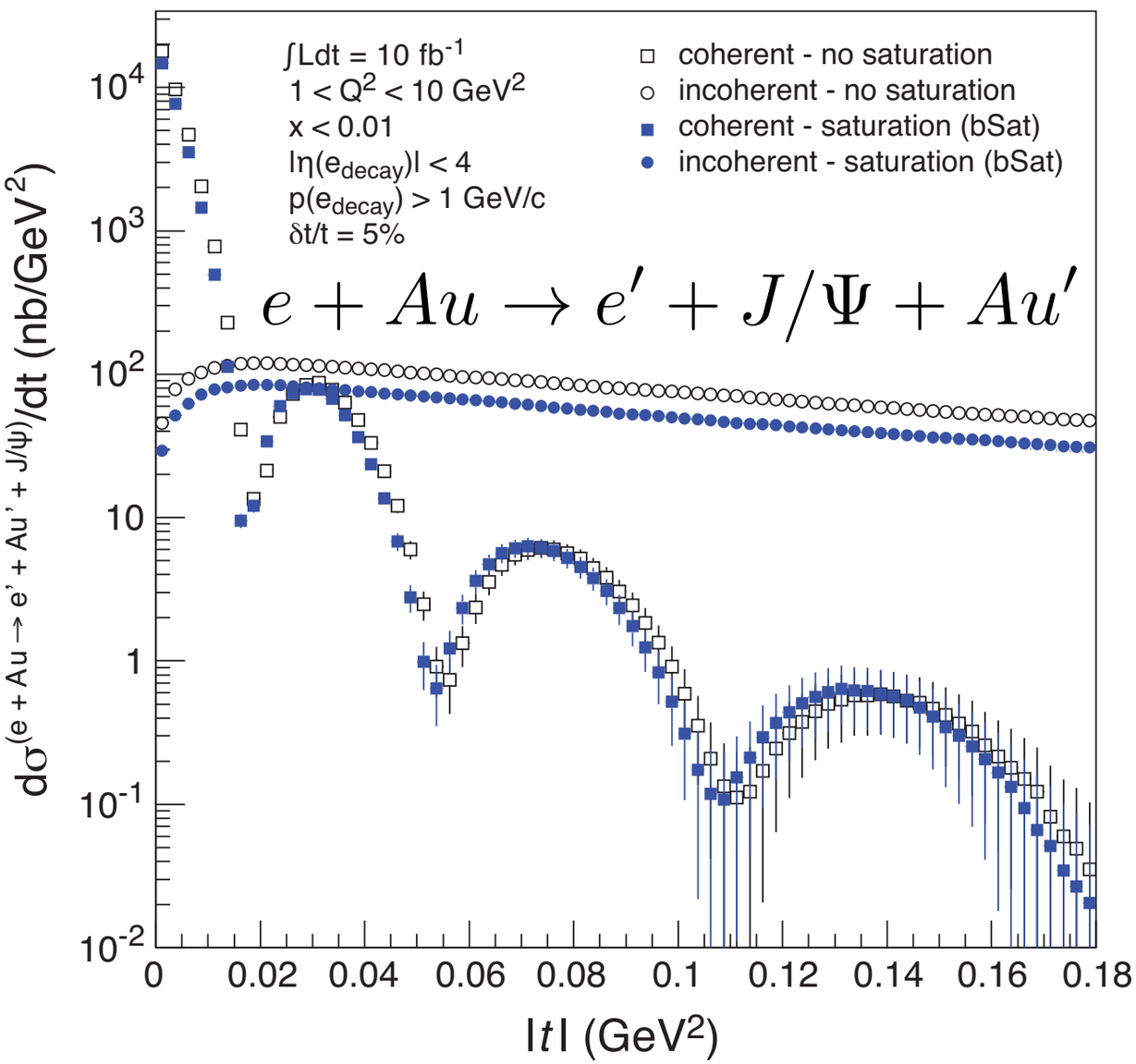


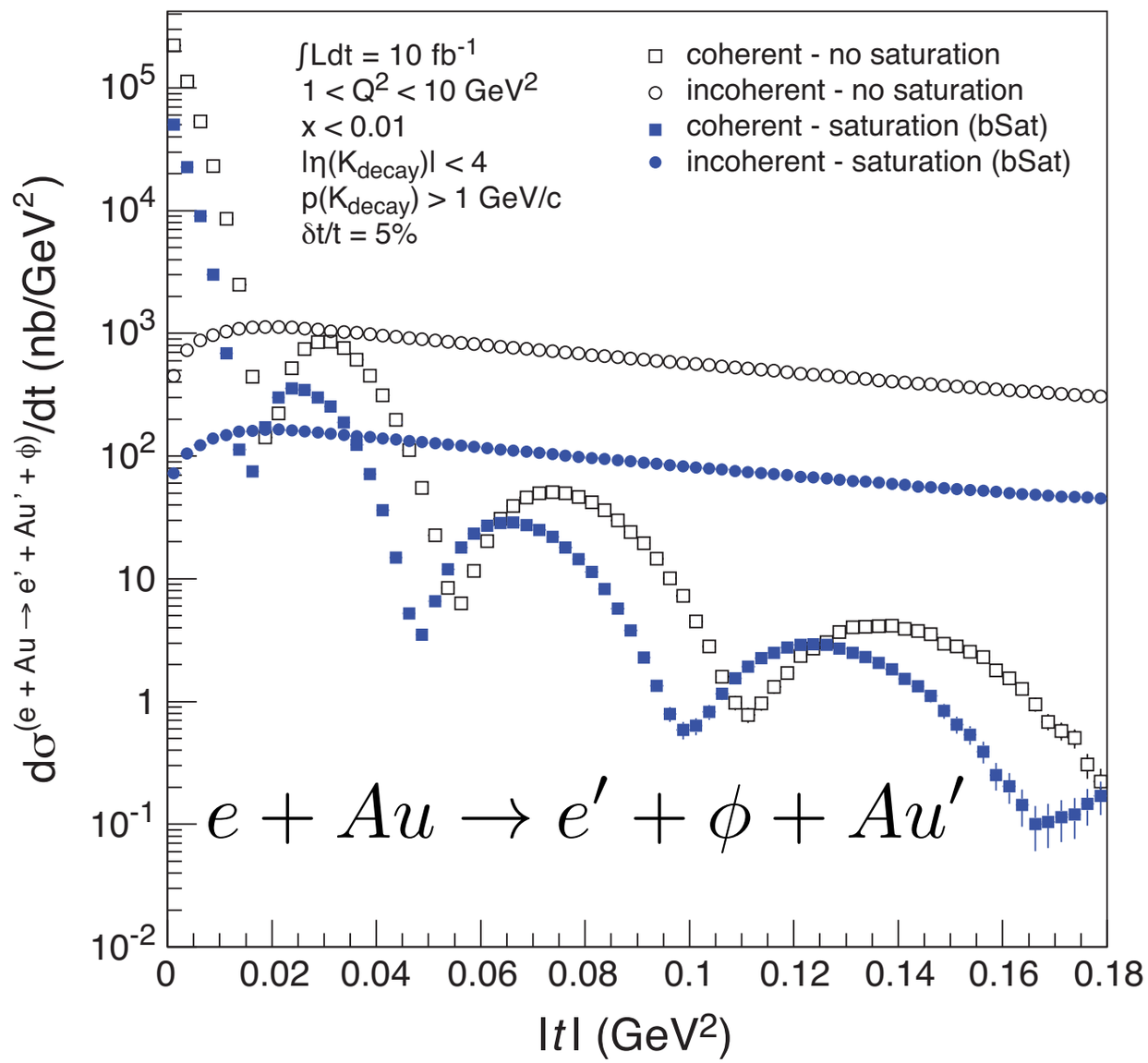




Probing the spatial gluon distribution at eRHIC

$$F(b) = \frac{1}{2\pi}\int_0^\infty \mathrm{d}\Delta\Delta J_0(\Delta b)\sqrt{\frac{\mathrm{d}\sigma_{\mathrm{coherent}}}{\mathrm{d}t}(\Delta)}\Bigg|_{\mathrm{mod}}$$





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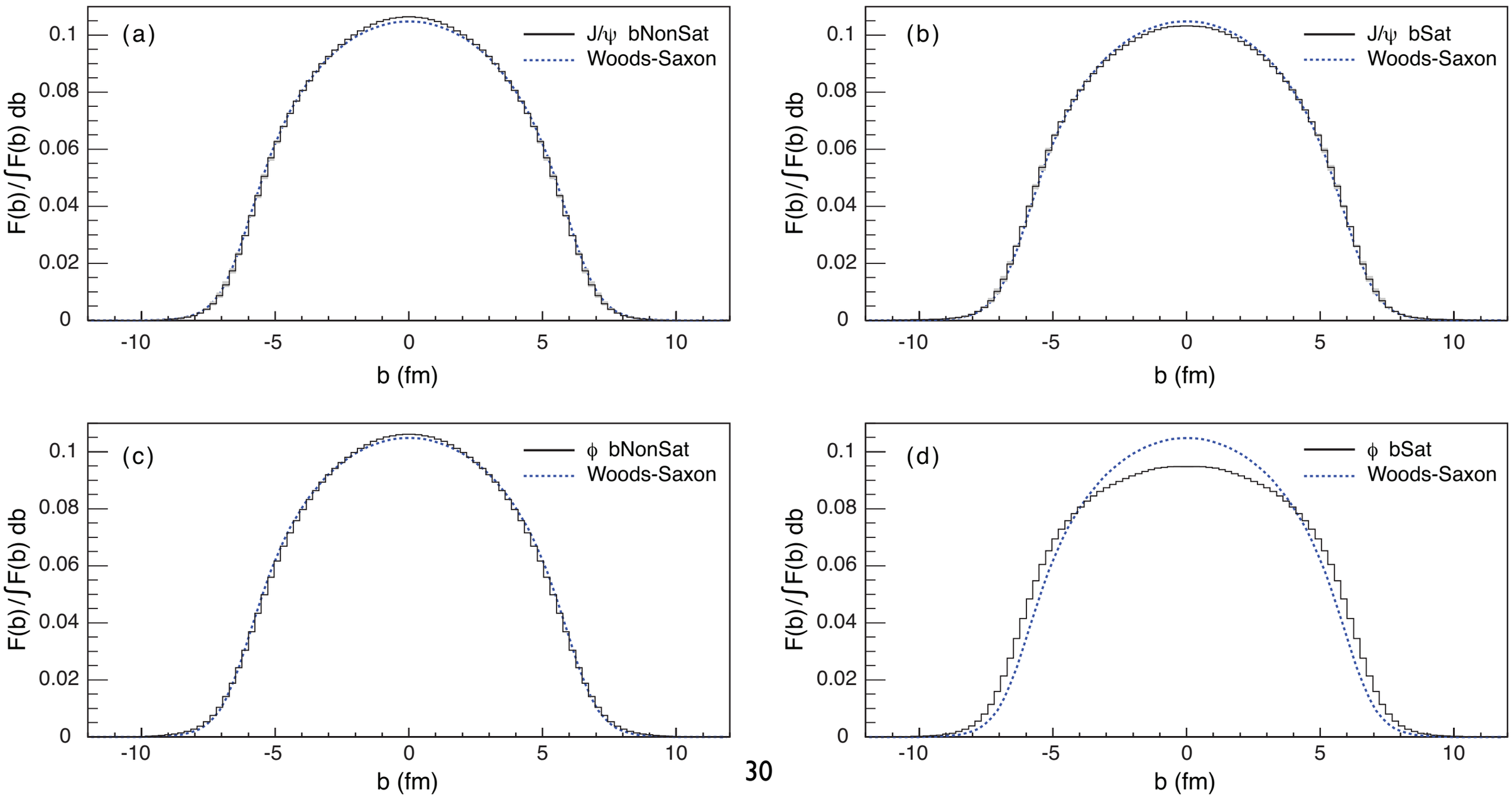

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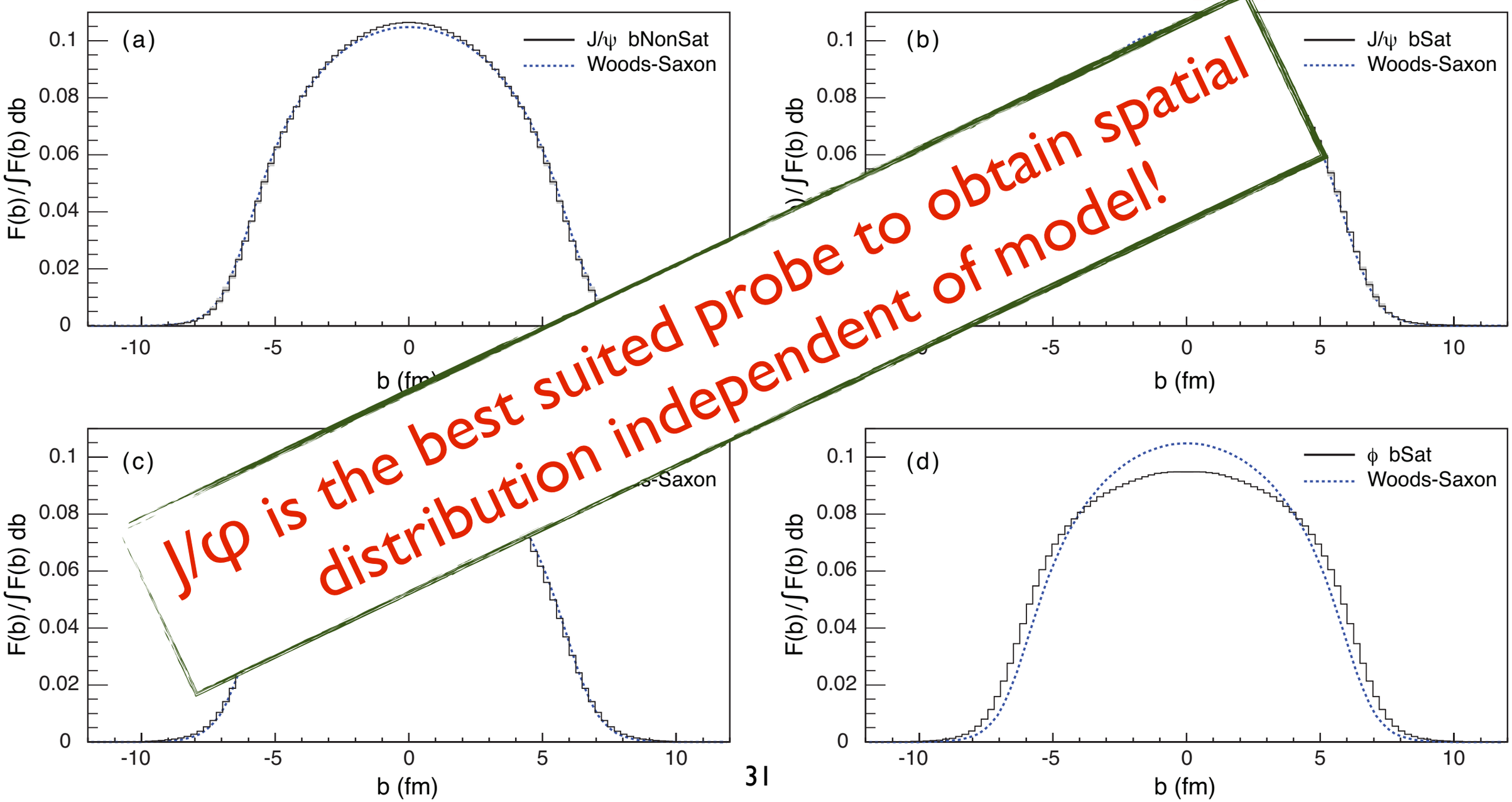

J/φ is the best suited probe to obtain spatial distribution independent of model!

Summary

Diffraction in eA is a great tool for measuring:

1. a signal for gluon saturation
2. gluon spatial distribution in nuclei

saturation signal, day 1 meaurement via diffractive/total ratio

gluon spatial distributions in nuclei available in a model independent way via exclusive heavy vector mesons, s.a. J/φ

eRHIC truly an ultra high resolution femtoscope for probing the initial state of nuclei